Jet Propulsion Laborator
California Institute of Technolog

Galactic Observations of Terahertz C+ Herschel Open Time Key Project

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got C+ ?®

Galactic Observations of Terahertz C+ Herschel Open Time Key Project

GOTC+ Team:

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Di Li
Harold Yorke
Jorge L. Pineda

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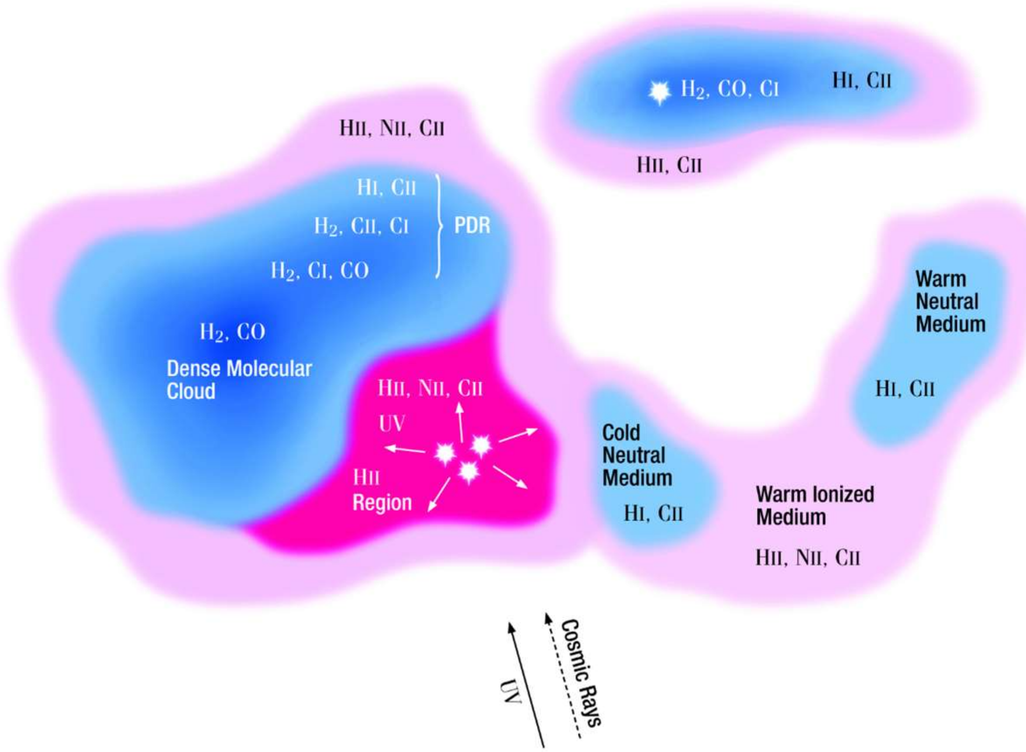
Outline

- What we learned from GOT C+.
- GOT C+ spin-offs.
- Beyond GOT C+: SOFIA M51 survey.

The [CII] 158um Line

- Carbon is the fourth most abundance chemical element in the universe.
- The C+ ion has one fine-structure transition at 158um.
- Carbon is singly ionized (C^+) in environments illuminated with far-ultraviolet radiation from massive stars.
- It is excited by collisions with e^-, H, and H_2, and therefore the [CII] line is a tracer of ionized gas regions, neutral atomic clouds, and diffuse molecular clouds (CO-dark H_2 clouds).

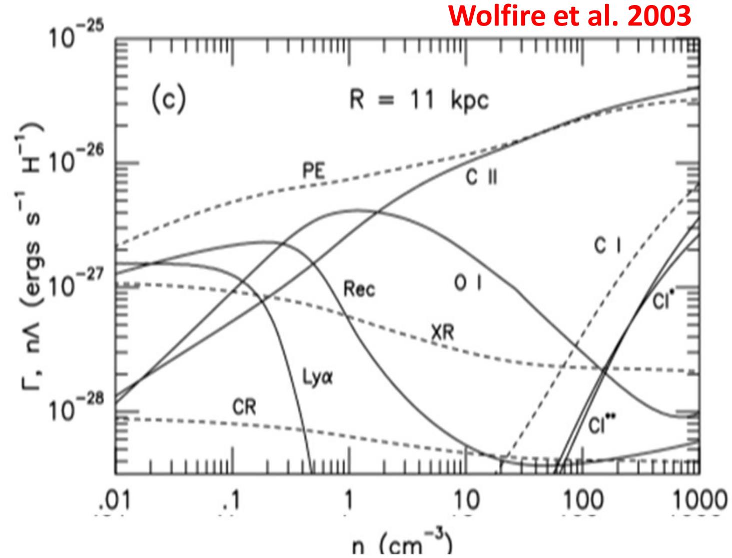


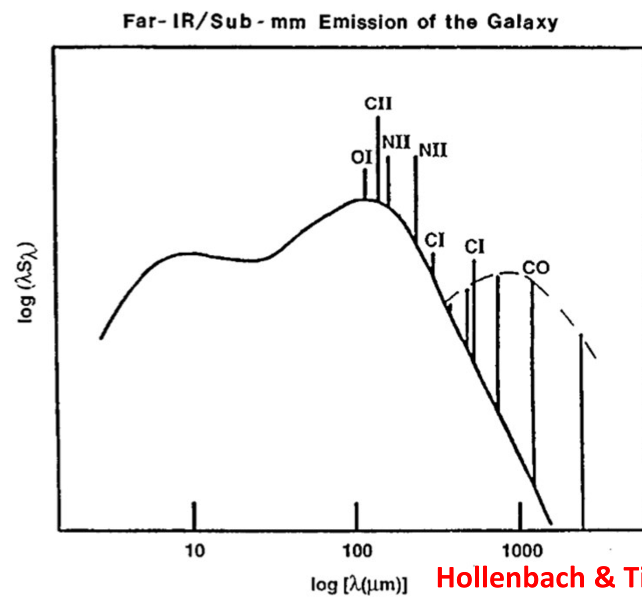
Photon-dominated region (PDR): Region where the chemistry and thermal balance is dominated by the far-ultraviolet radiation field from massive stars.

The [CII] 158um Line

- The [CII] line is the main coolant of the interstellar medium, and therefore reflects the energy input from massive stars into the ISM.
- It represents 0.1 to 1% of the total far-infrared continuum, and it is the brightest FIR line.
- Thus, the CII line is a tracer of star formation in galaxies.

Wolfire et al. 2003





Hollenbach & Tielens 1999

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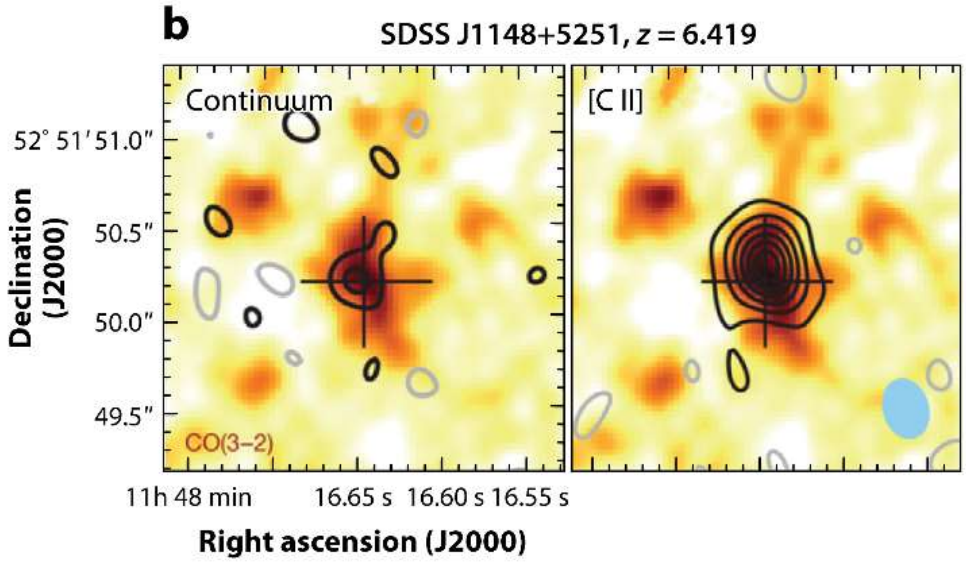

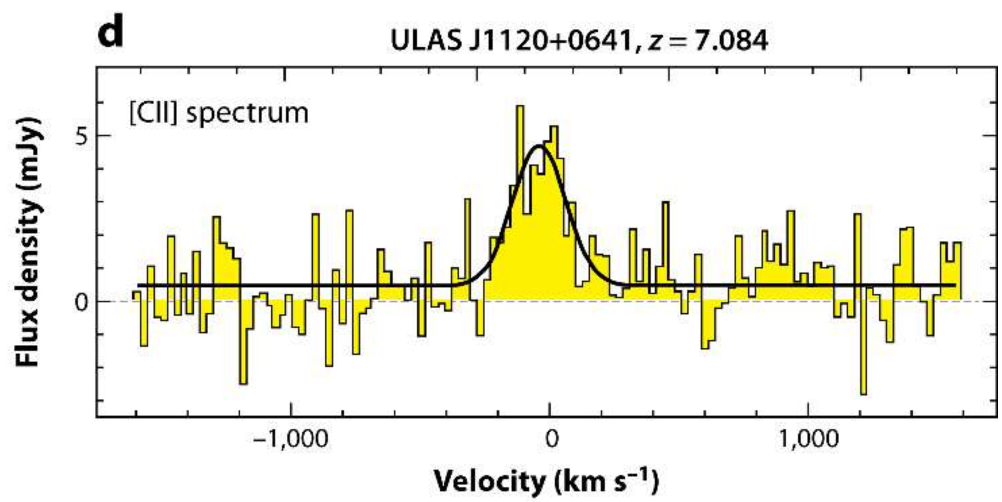

Wang et al. 2013 ApJ 773, 44

The [CII] 158um Line

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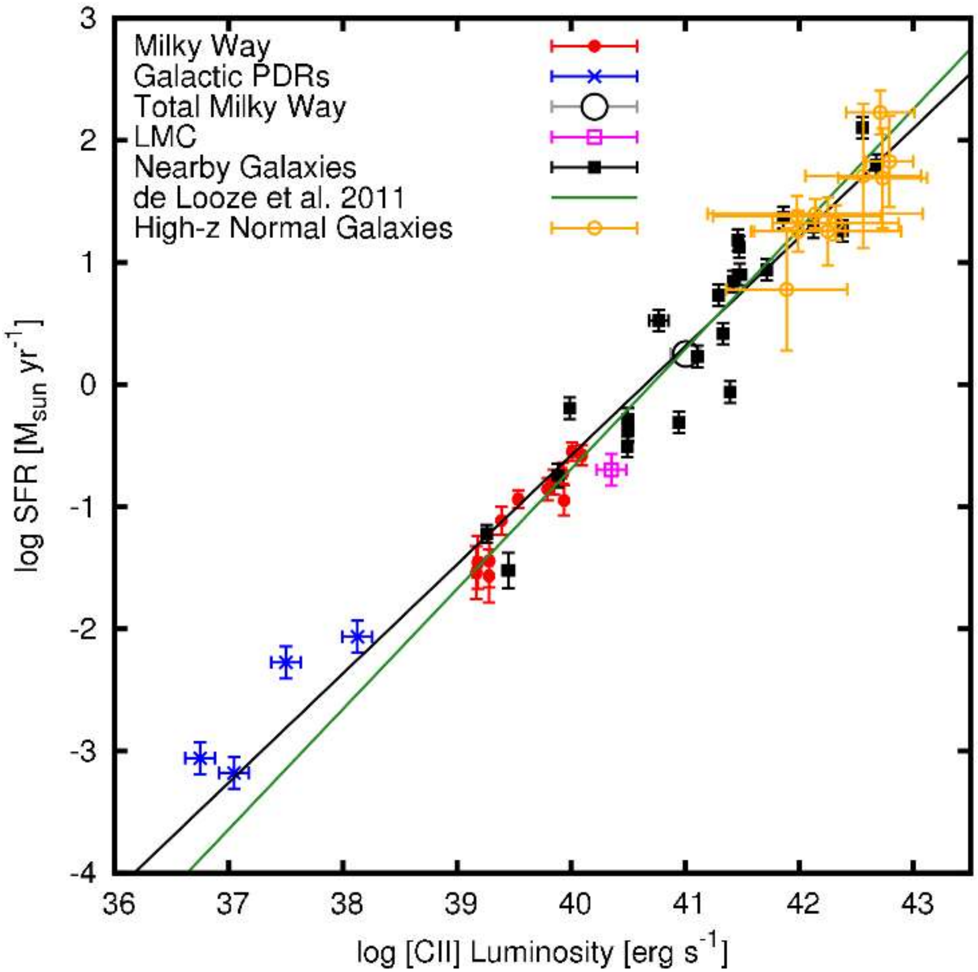
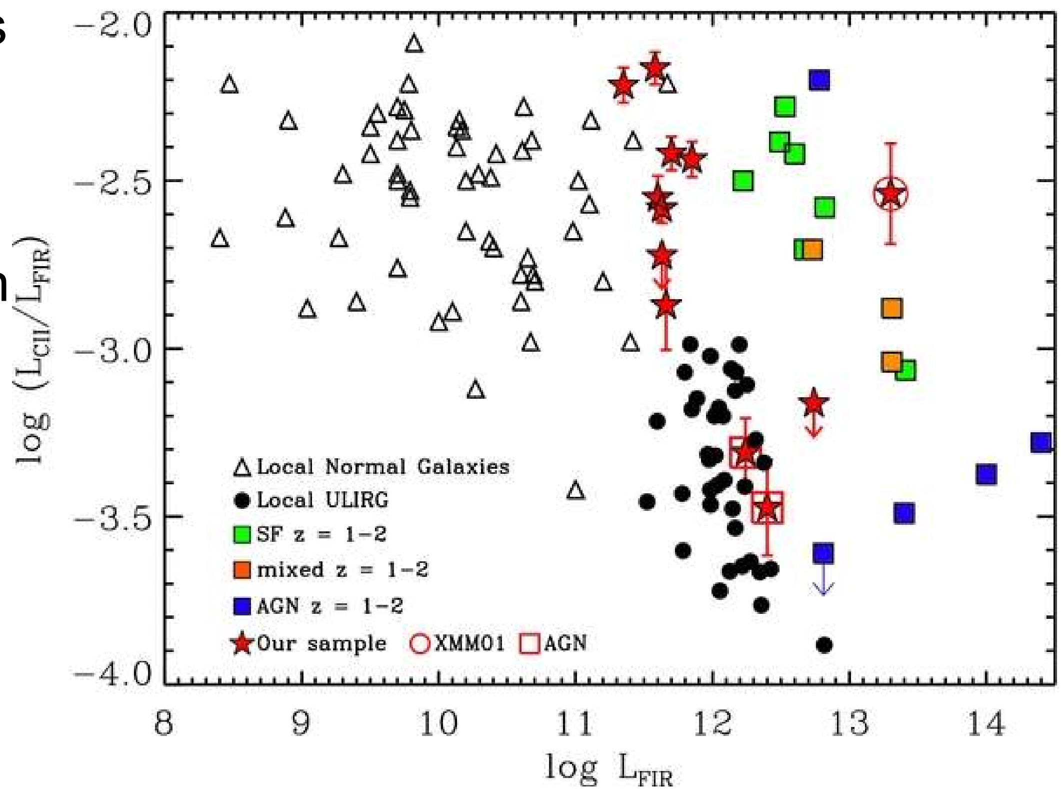


Pineda et al. 2014 A&A 570, A121

The [CII] 158um Line

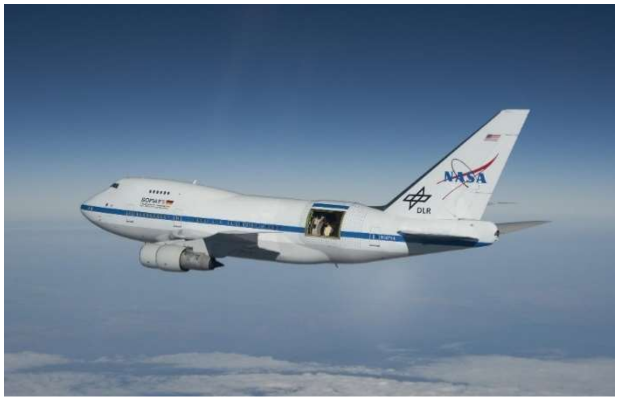
- The [CII] line is the main coolant of the interstellar medium, and therefore reflects the energy input from massive stars into the ISM.
- It represents 0.1 to 1% of the total far-infrared continuum, an it is the brightest FIR line.
- Thus, the CII line is a tracer of star formation in galaxies.
- But a [CII]/FIR deficit is observed in ultra luminous infrared galaxies.



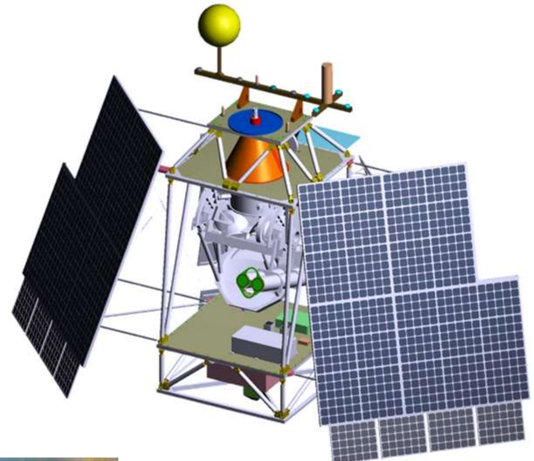
Rigopoulou et al. 2015

Luhman et al (1998) – ULIRGs (see also Malhotra et al. 1997)

The study of the [CII] 158um has motivated several space and sub-orbital missions.



SOFIA

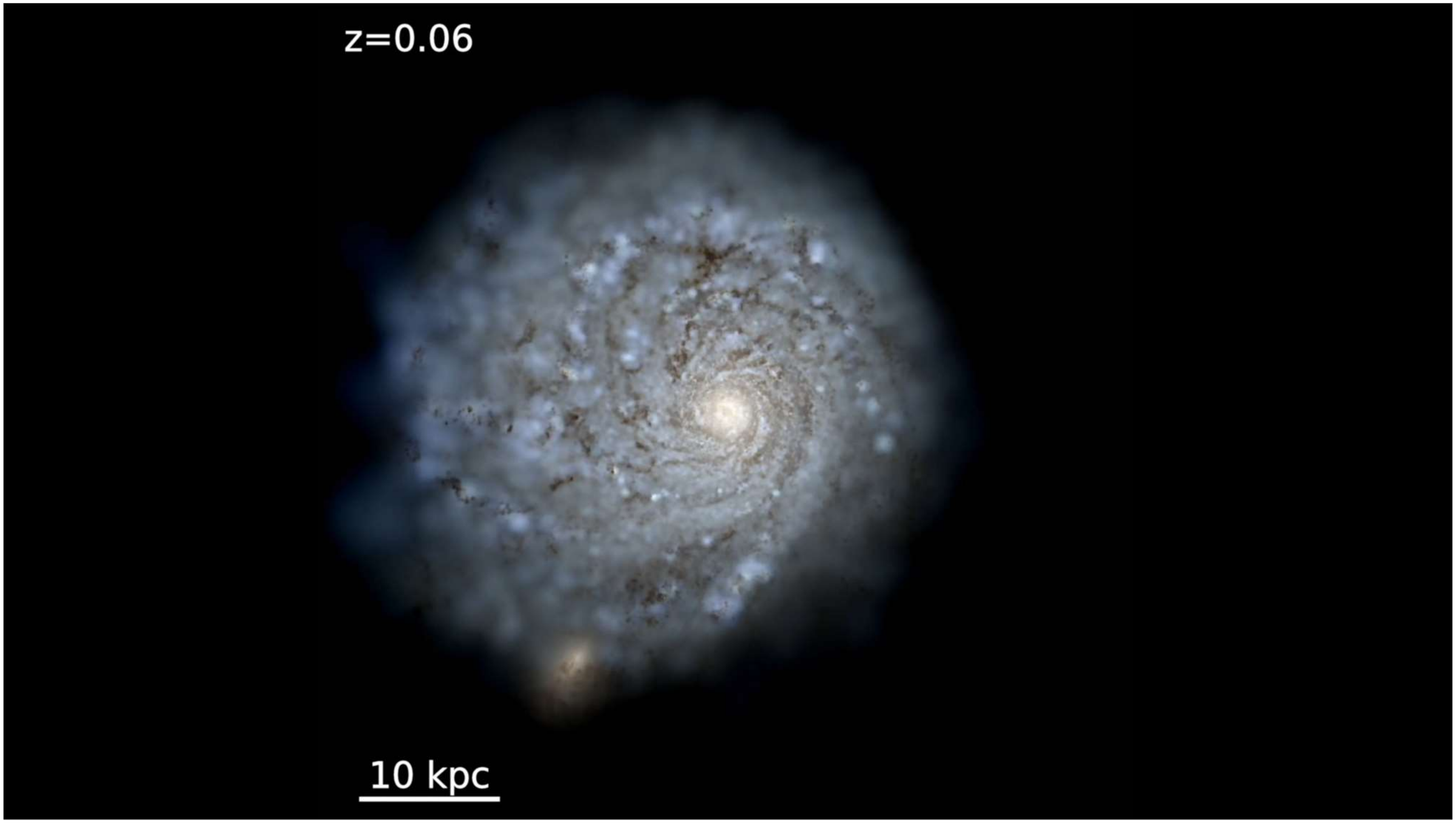


GUSTO

ALMA: [CII] at high-Z

Herschel

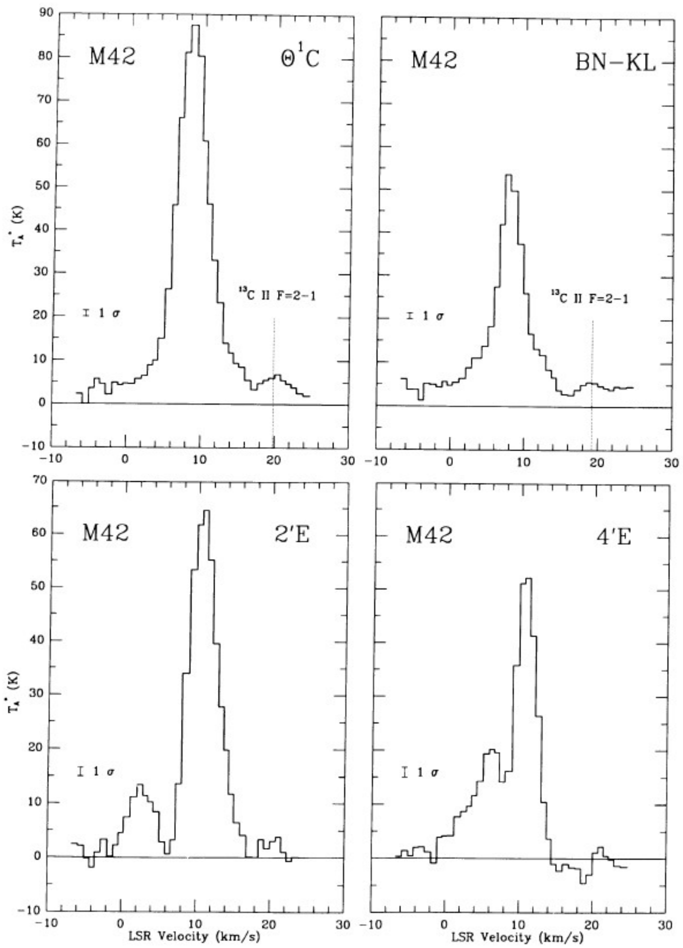
The study of the [CII] 158um has also motivated theoretical work



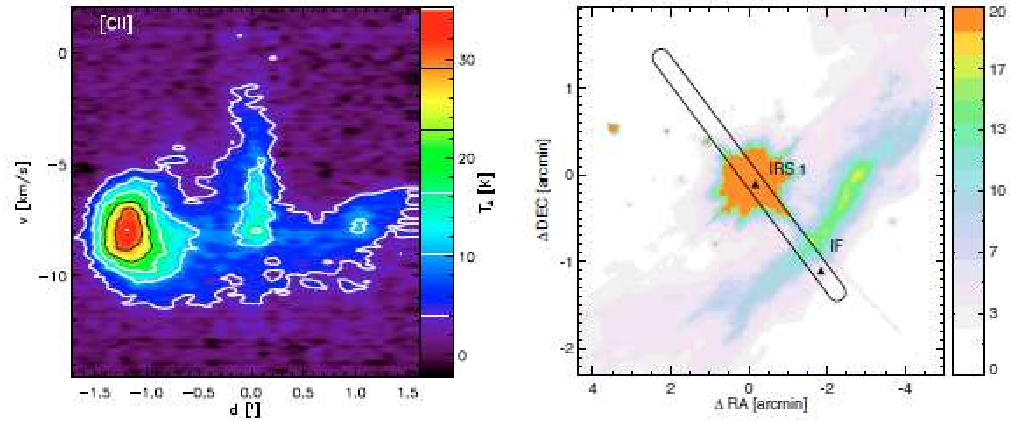
FIRE Simulation (Hopkins et al. 2014)

Orr et al. 2019 in preparation

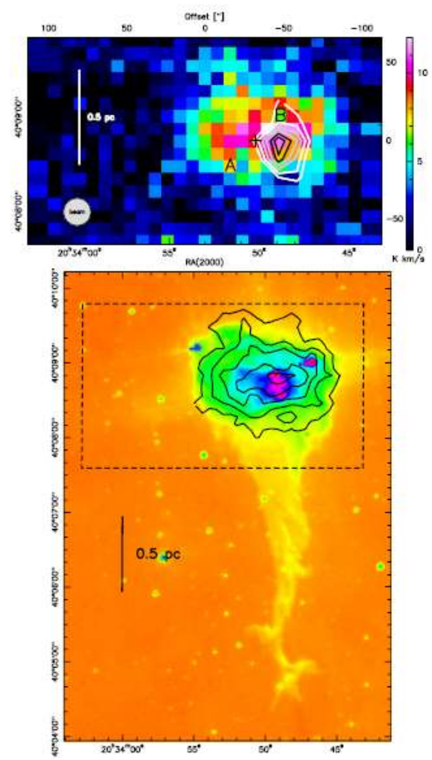
Photon Dominated Regions (PDRs)



KAO: e.g. Boreiko et al. 1998

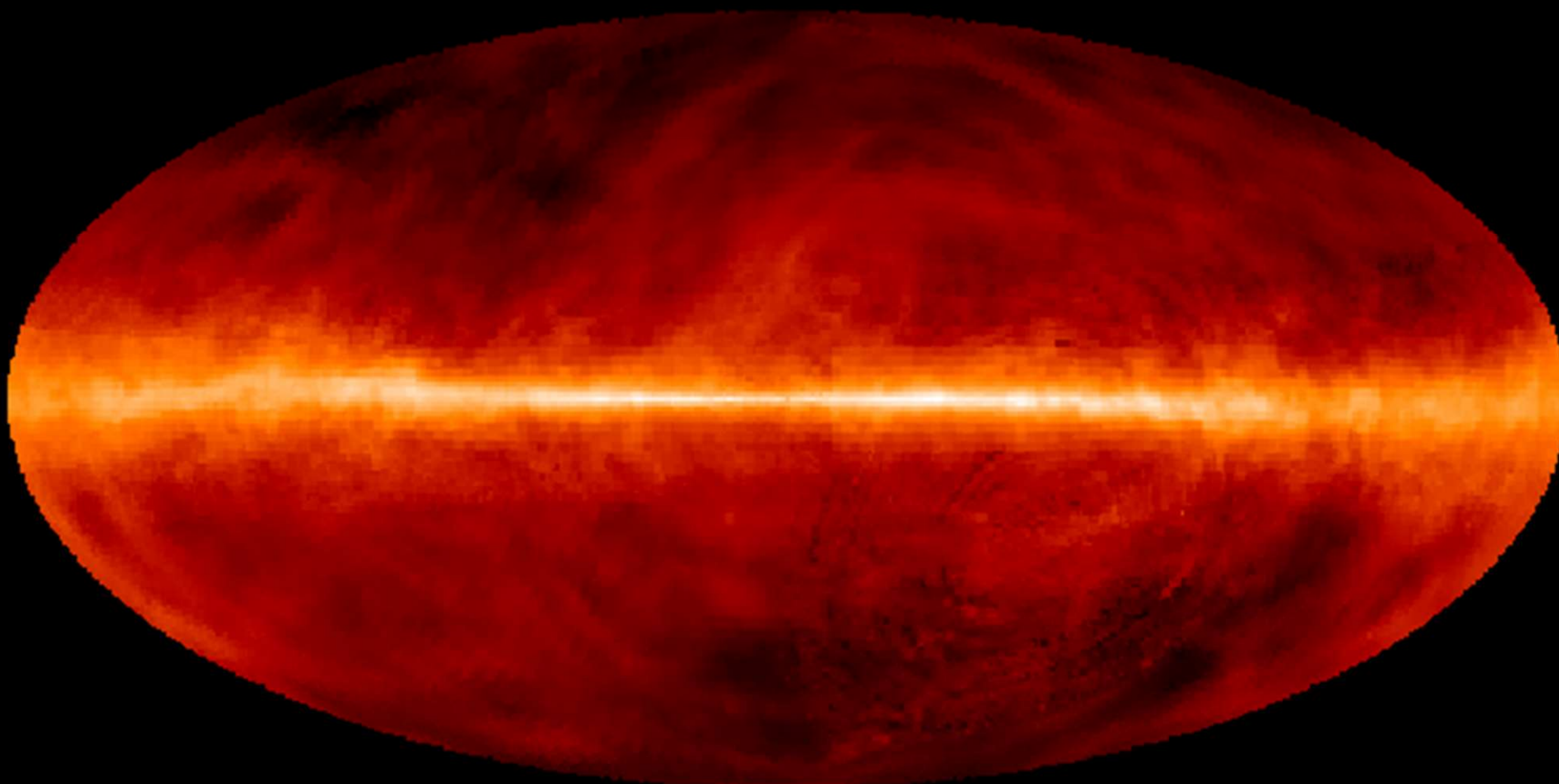


Herschel/WADI ; e.g. Dedes et al. 2010



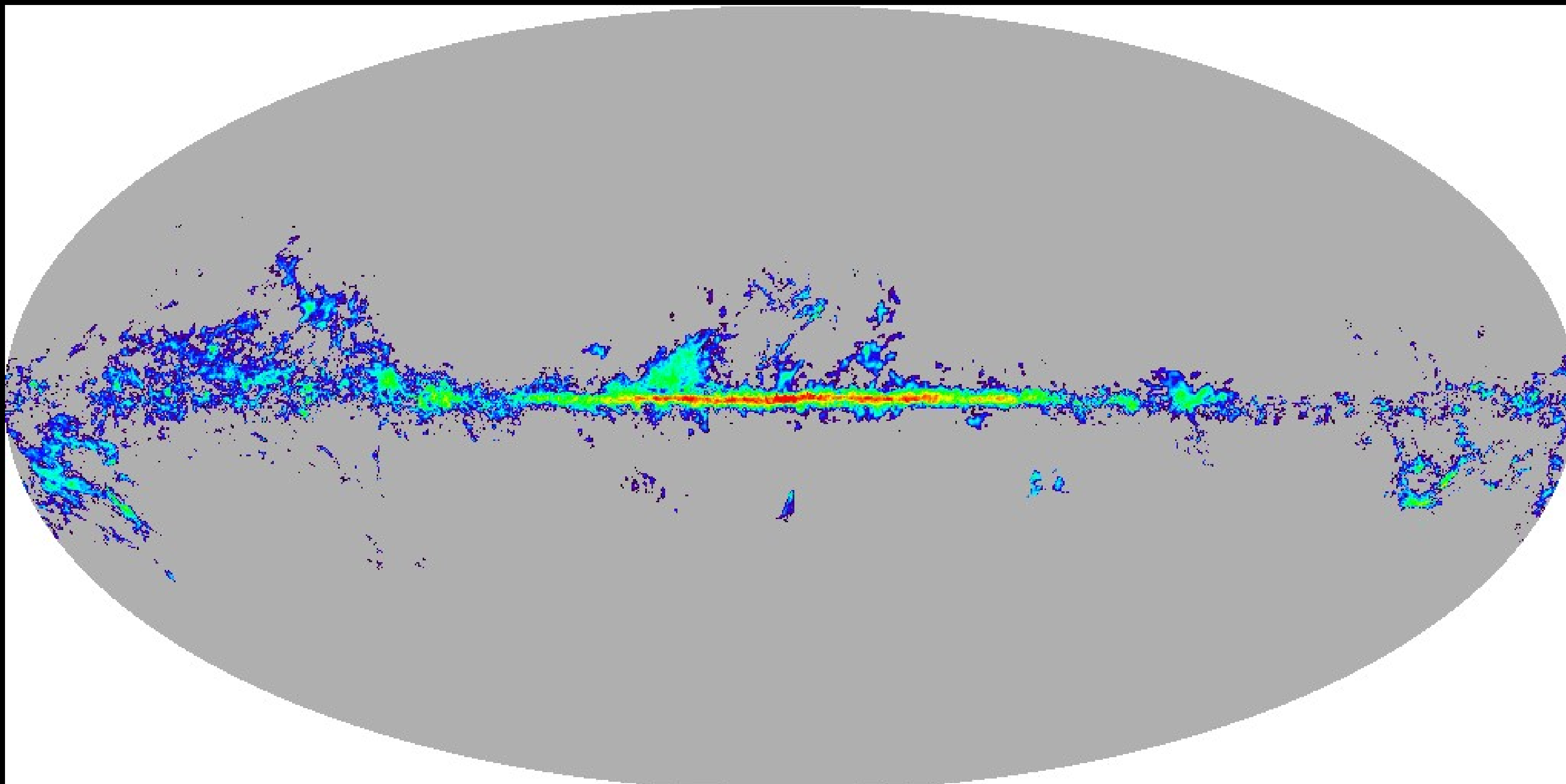
SOFIA ;
e.g. Schneider et al. 2012

The Milky way in atomic hydrogen gas (HI)



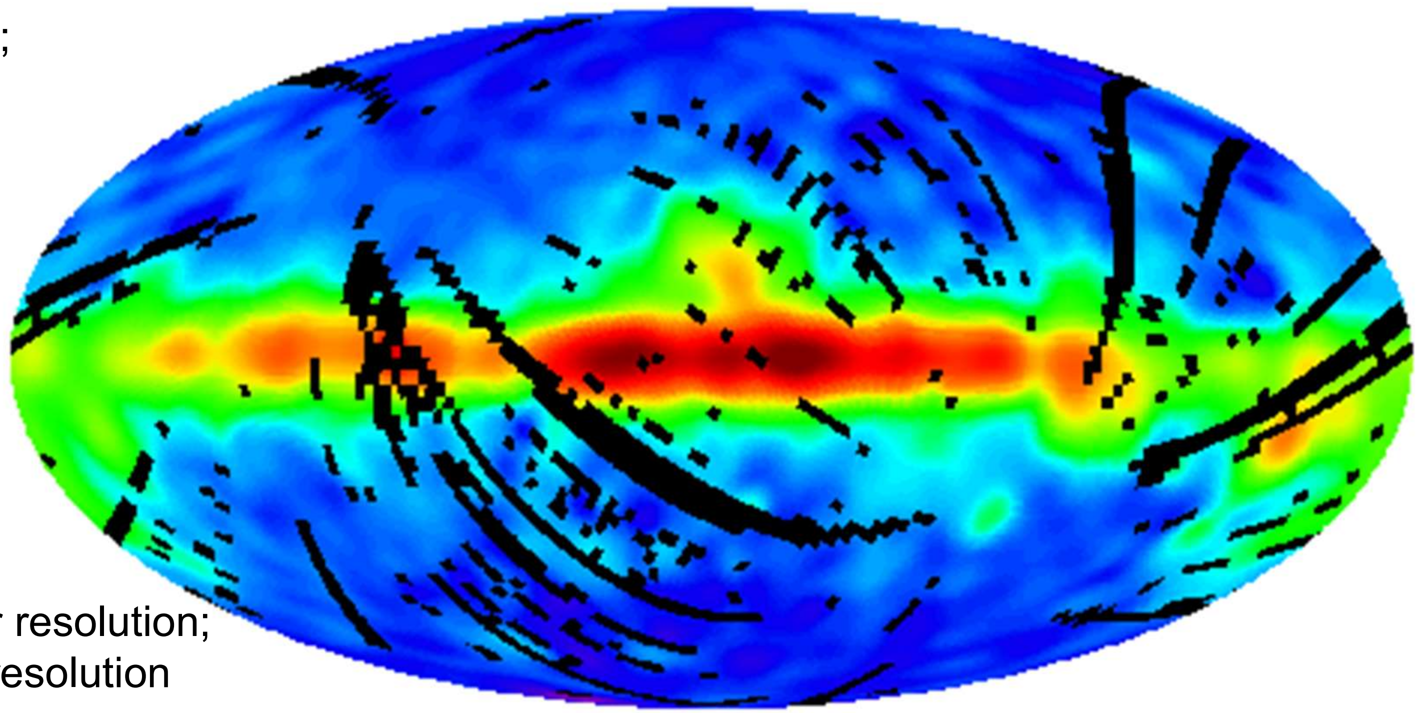
The Milky way in molecular hydrogen gas (traced by CO)

Galactic Latitude (degrees)



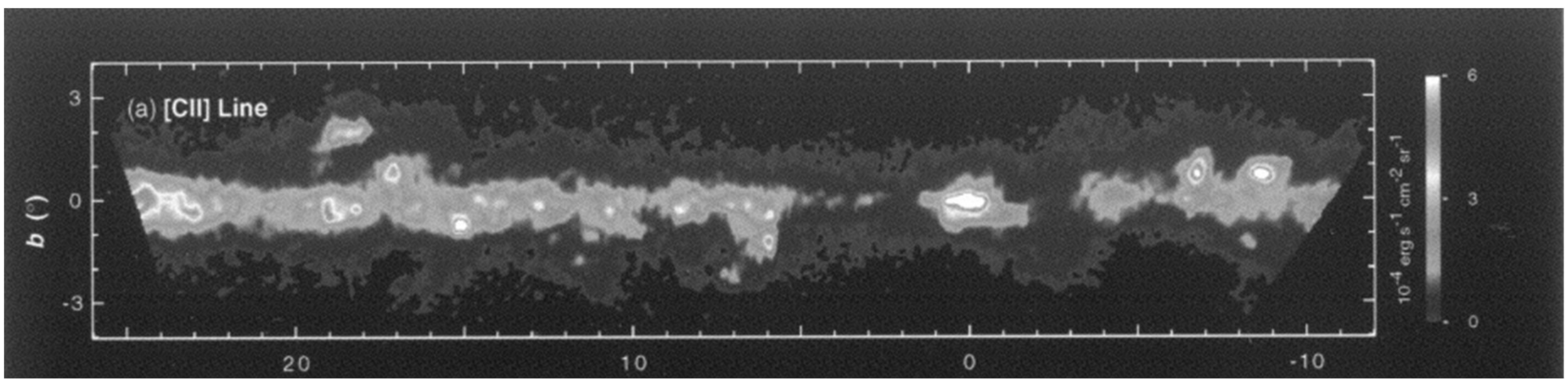
Galactic Longitude (degrees)

COBE FIRAS 158 μm C^+ Line Intensity



COBE/FIRAS (1989);
7 degree angular resolution;
1000 km/sec velocity resolution

BICE (1991);
15 arcminute angular resolution;
175 km/sec velocity resolution



Galactic Longitude [Degrees]

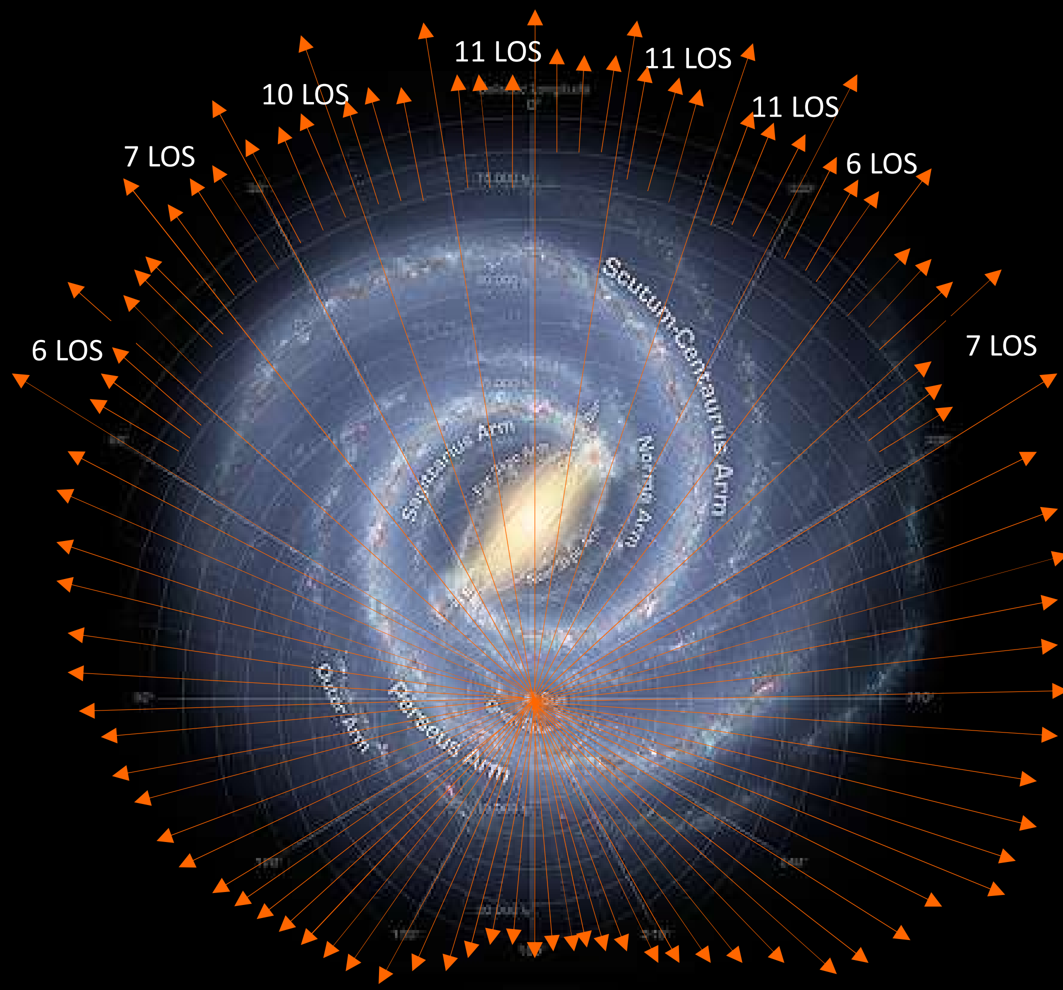
GOT C+ [CII] 1.9 THz Survey

GOT C+ is a volume weighted sample of ≈500 LOSs in the disk of the Milky Way.

We sample the Galactic plane every one degree in the inner galaxy and every two in the outer galaxy.

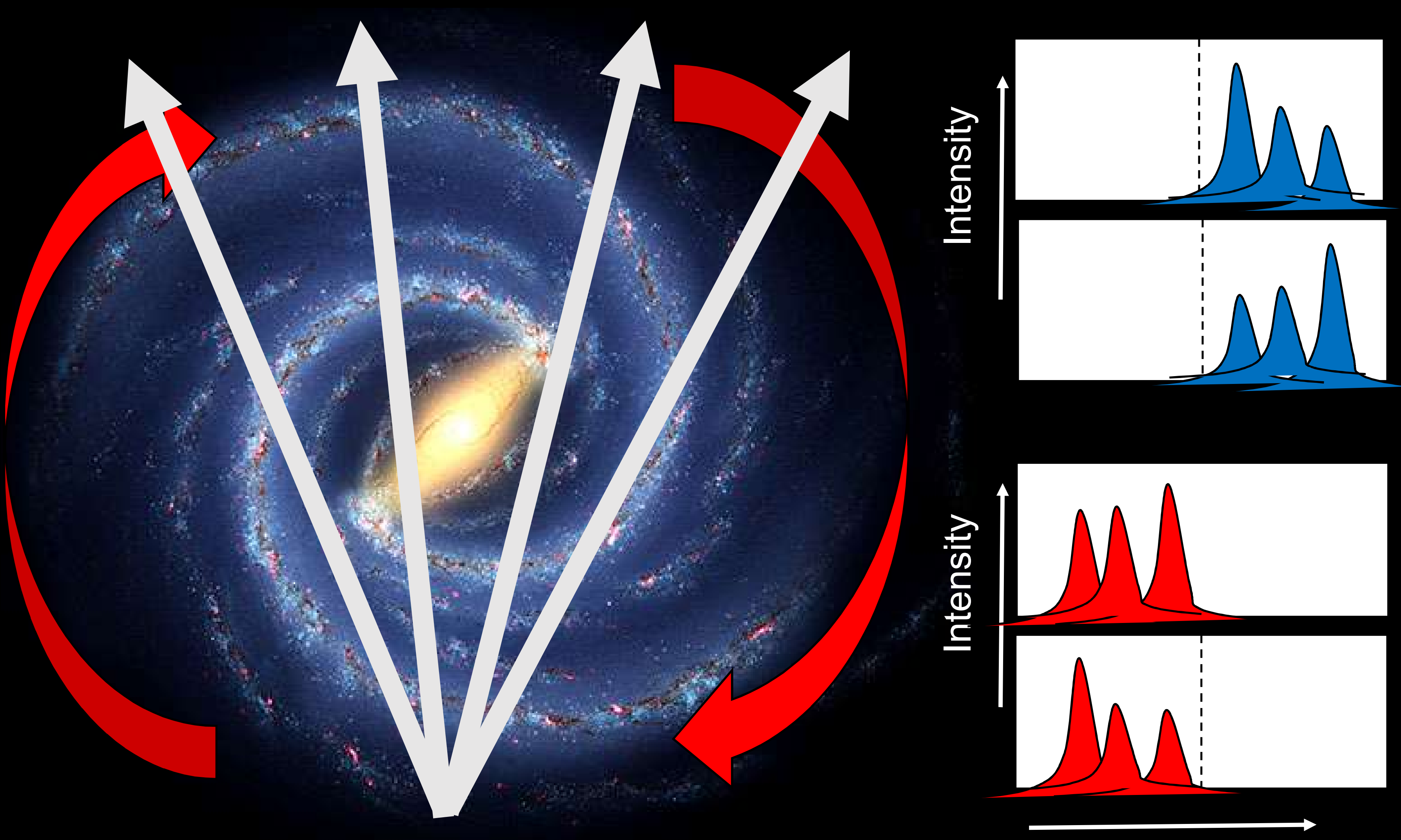
GOAL: Sample as many different clouds as possible over a wide range of physical conditions.

This allow us to obtain statistical information about the clouds in the Milky Way.



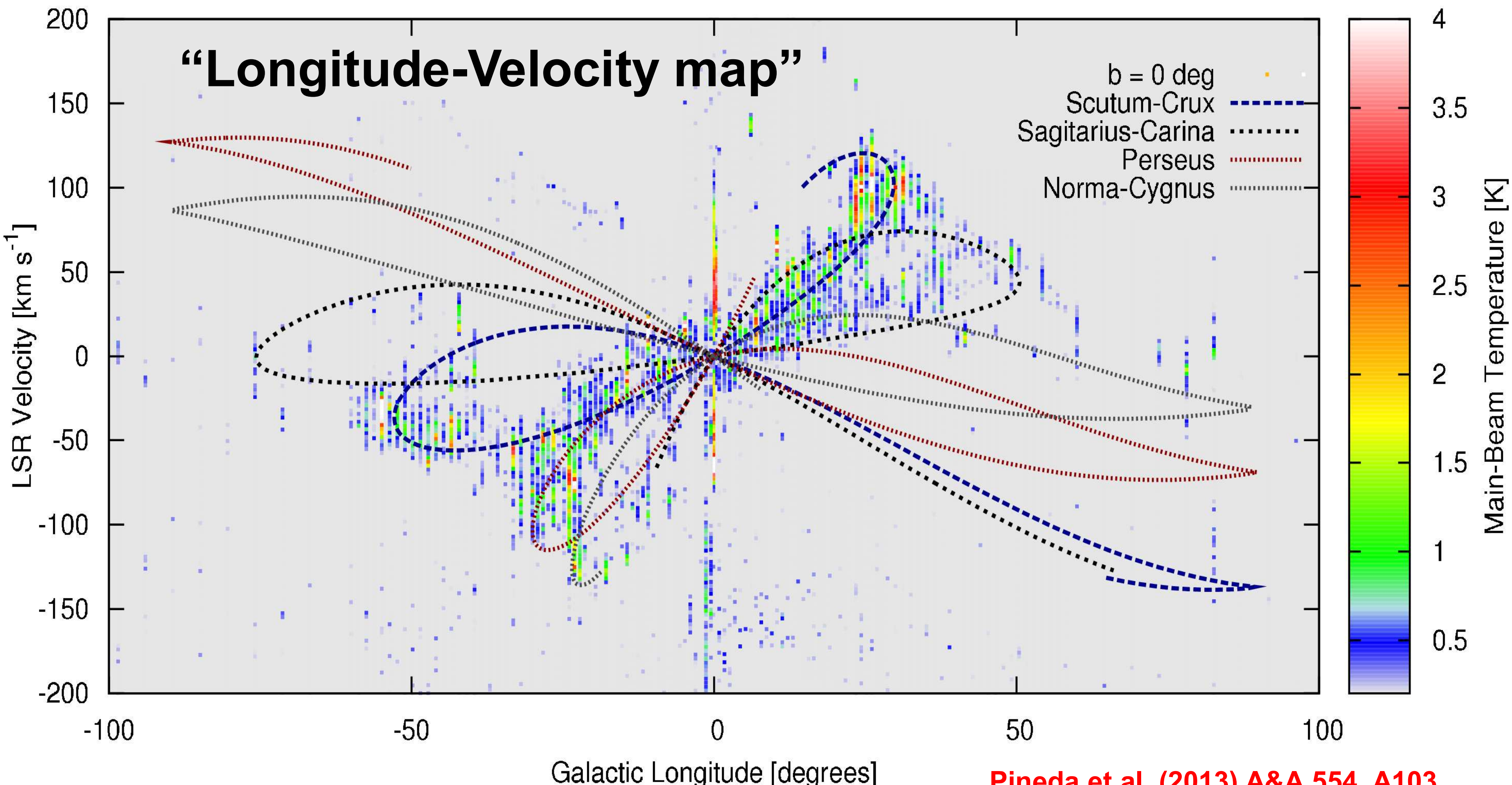
The rotation of the Milky Way

The rotation of the Milky Way



Differential rotation

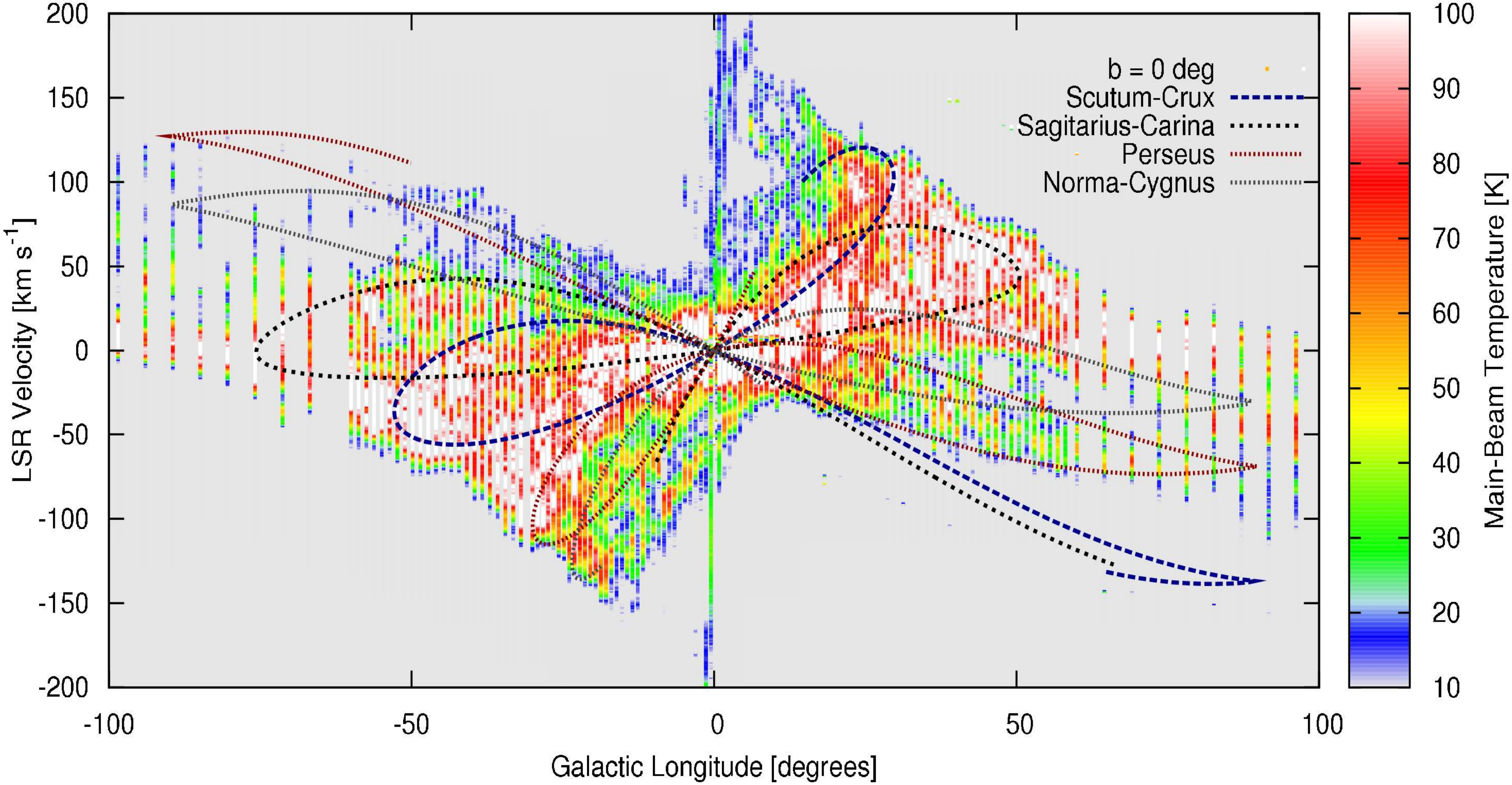
First observation of the line-of-sight [CII] distribution of the Milky Way:



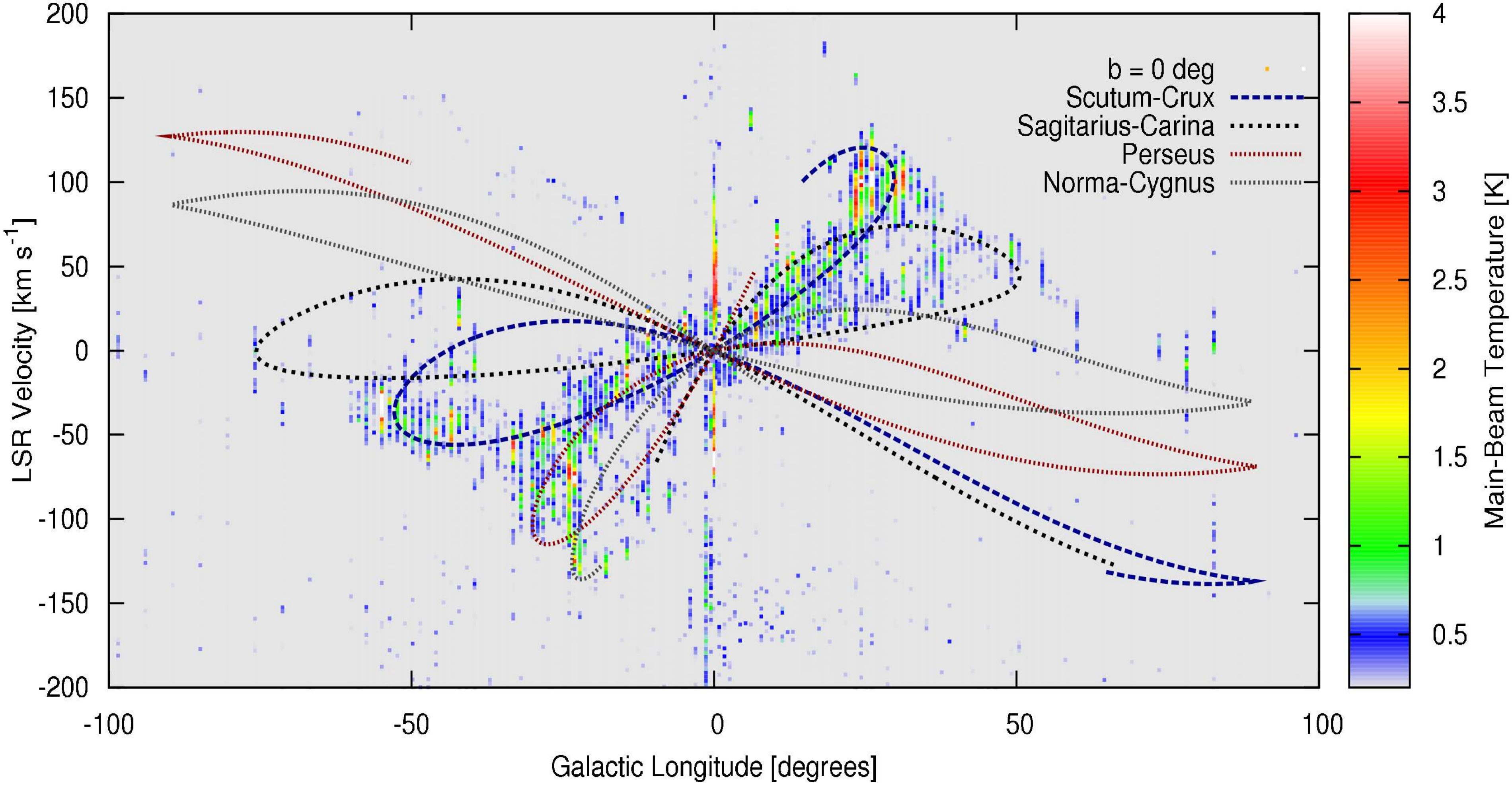
Pineda et al. (2013) A&A 554, A103

The lines are projection of the Milky Way's spiral arms into the Longitude-Velocity map.

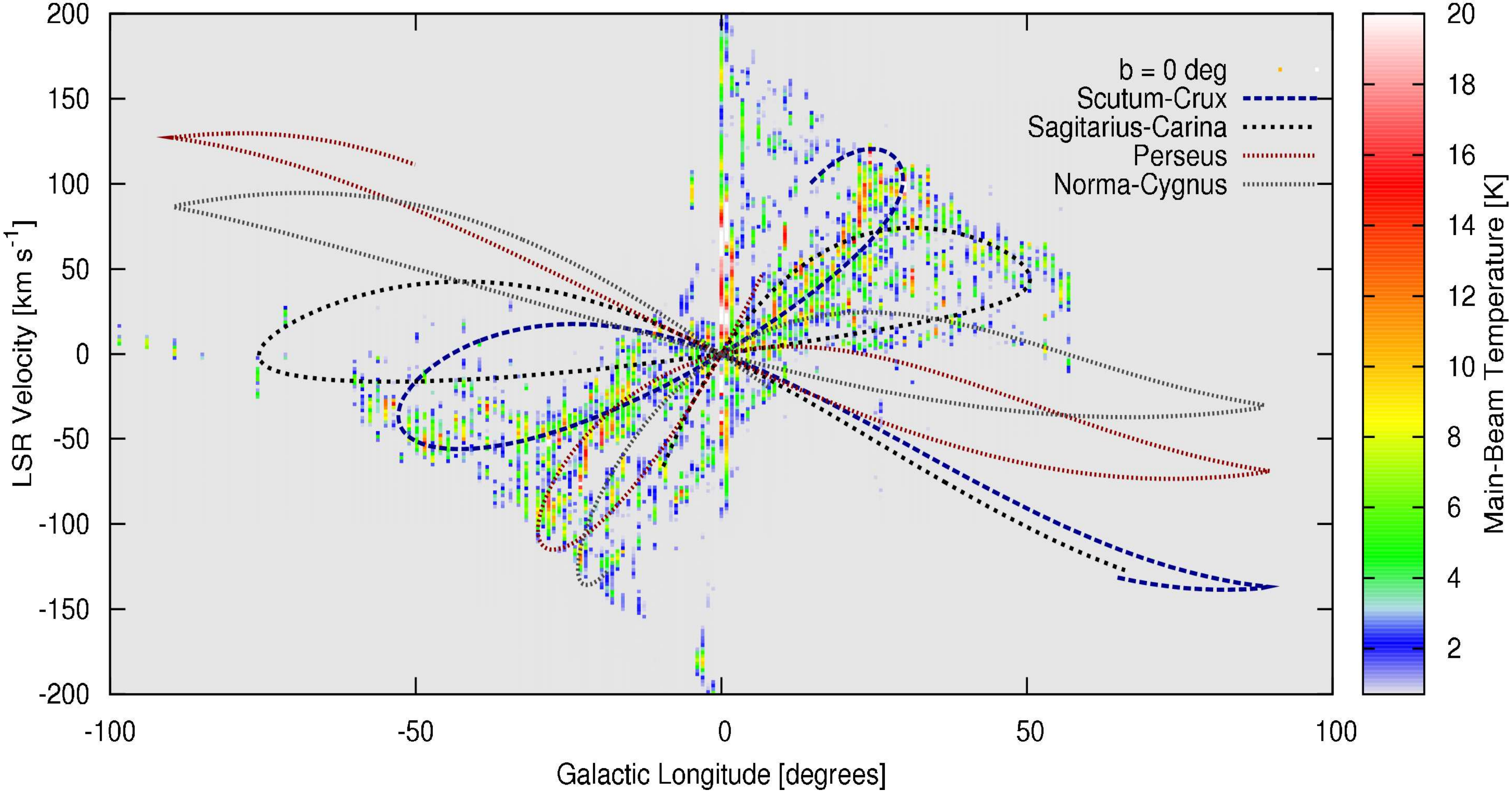
Atomic Gas (HI)



GOT C+ [CII] Distribution in the Milky Way

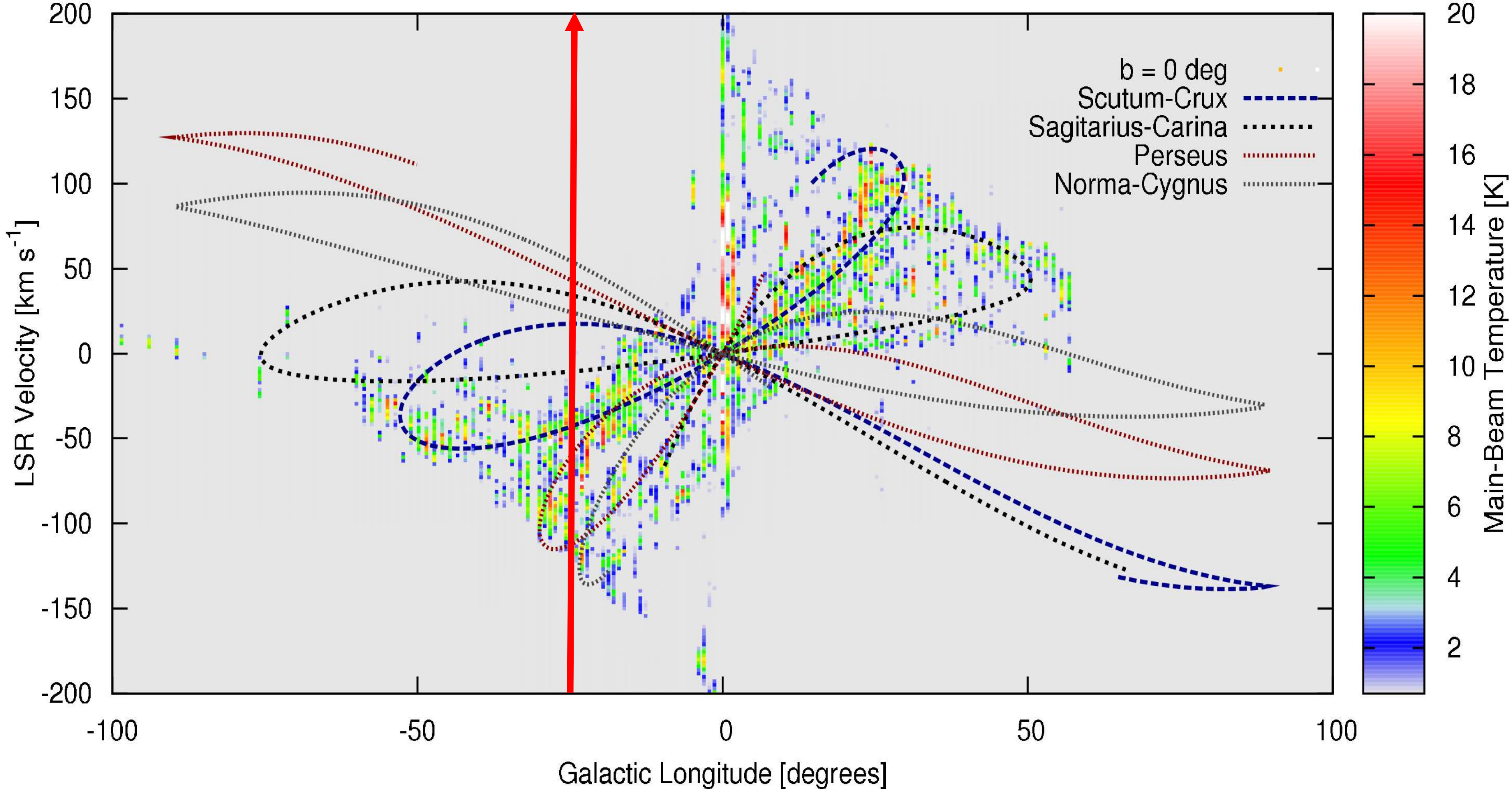


Dense and Cold Molecular Gas (CO)



[CII] traces the transition between atomic and molecular clouds.

Dense and Cold Molecular Gas (CO)



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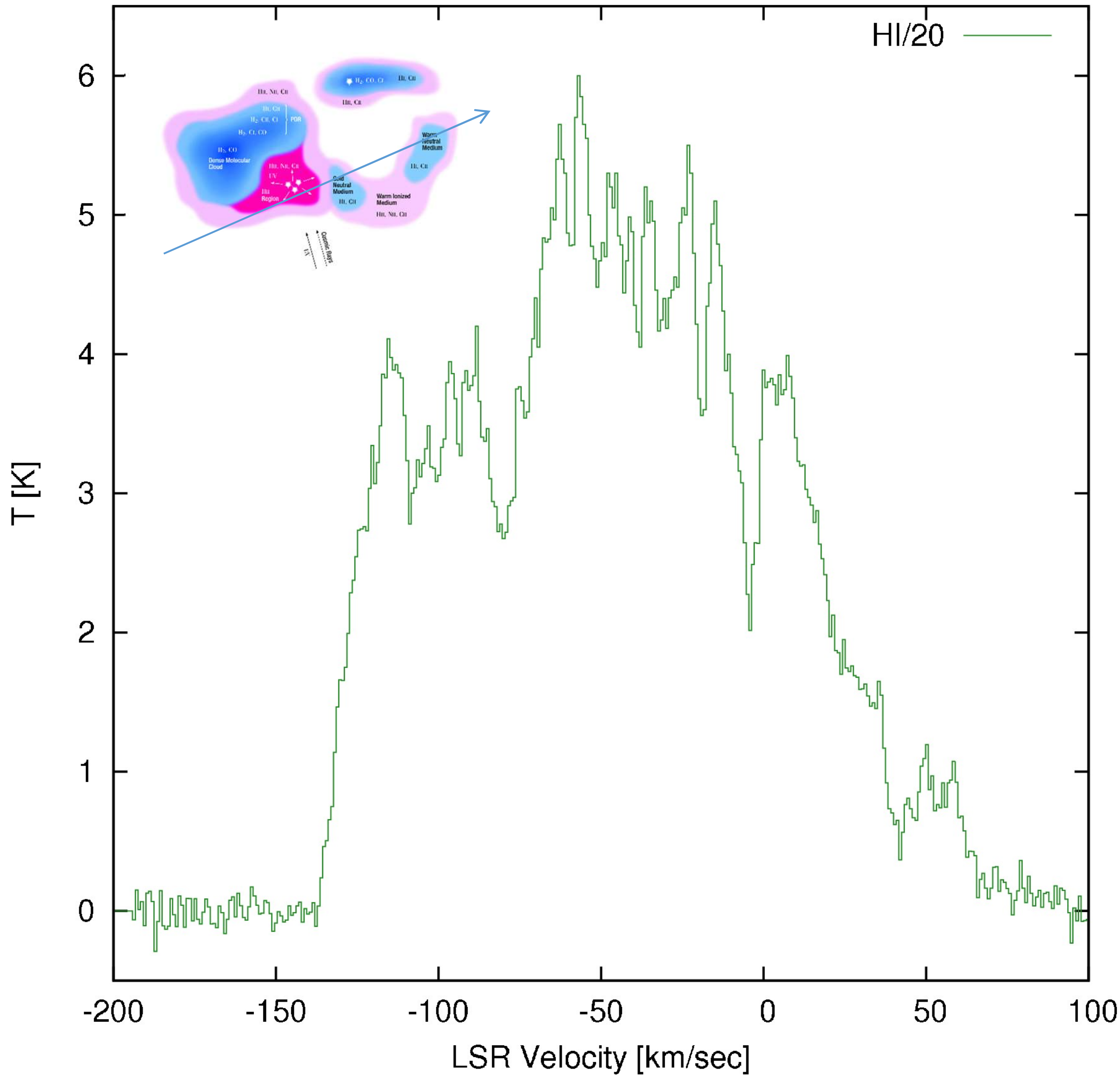
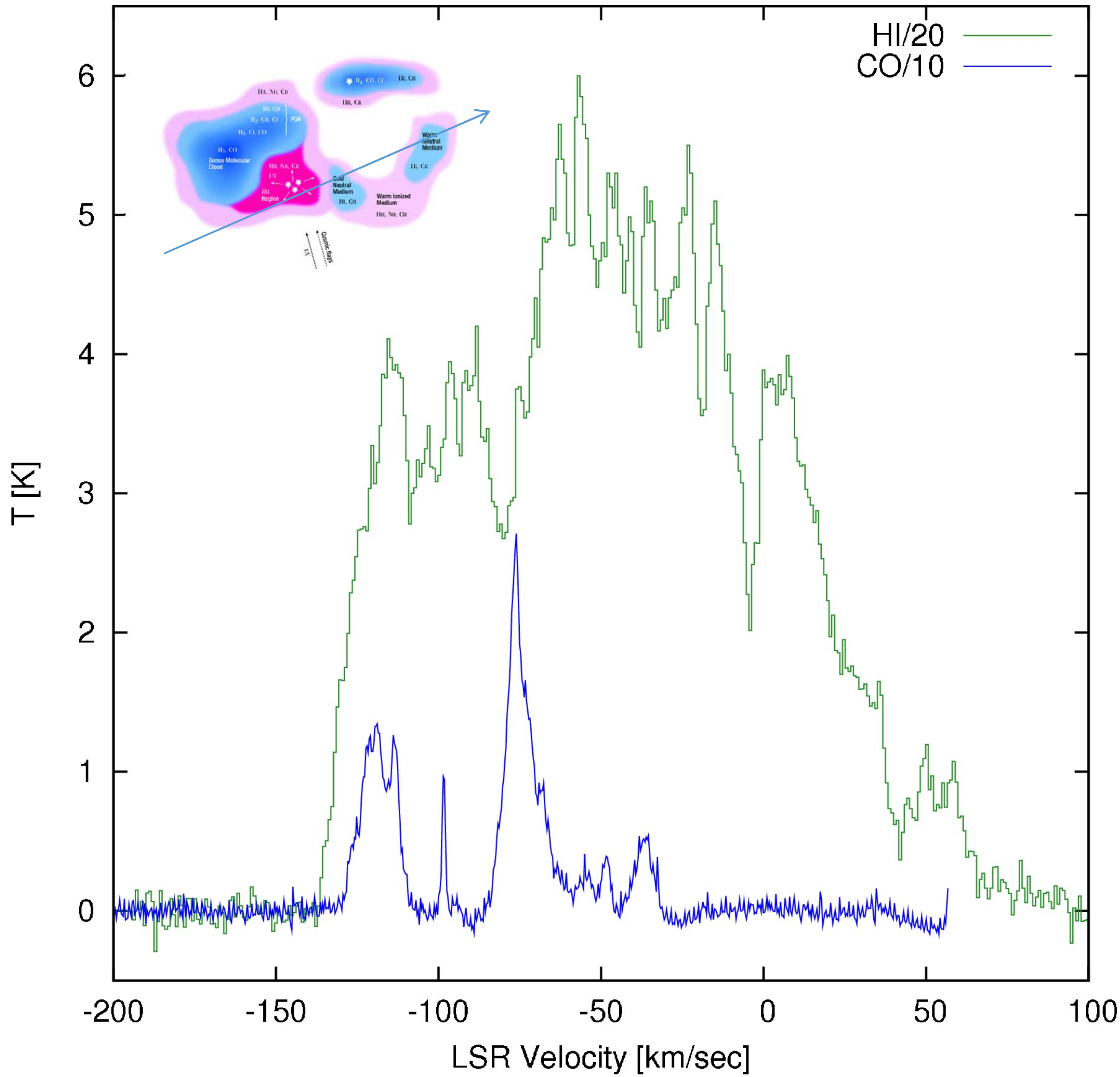

HI/20
T [K]
LSR Velocity [km/sec]
6
5
4
3
2
1
0
-200
-150
-100
-50
0
50
100
Dense Molecular Cloud
PDR
HII Region
UV
Cold Neutral Medium
Warm Neutral Medium
Warm Ionized Medium
Cosmic Rays


HI/20
CO/10
T [K]
LSR Velocity [km/sec]
-200
-150
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-50
0
50
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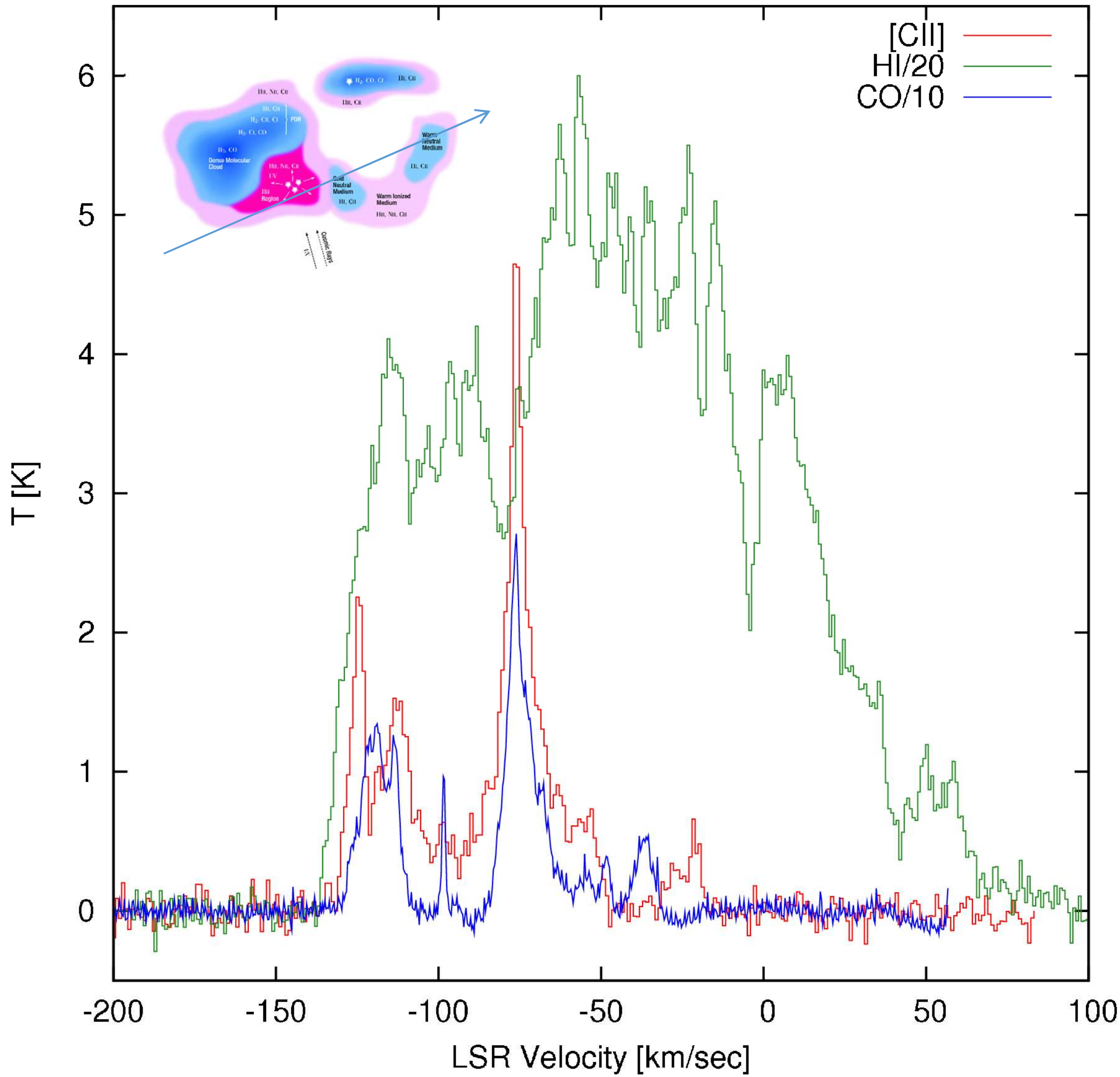
[CII]
HI/20
CO/10
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-200
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Dense Molecular Cloud
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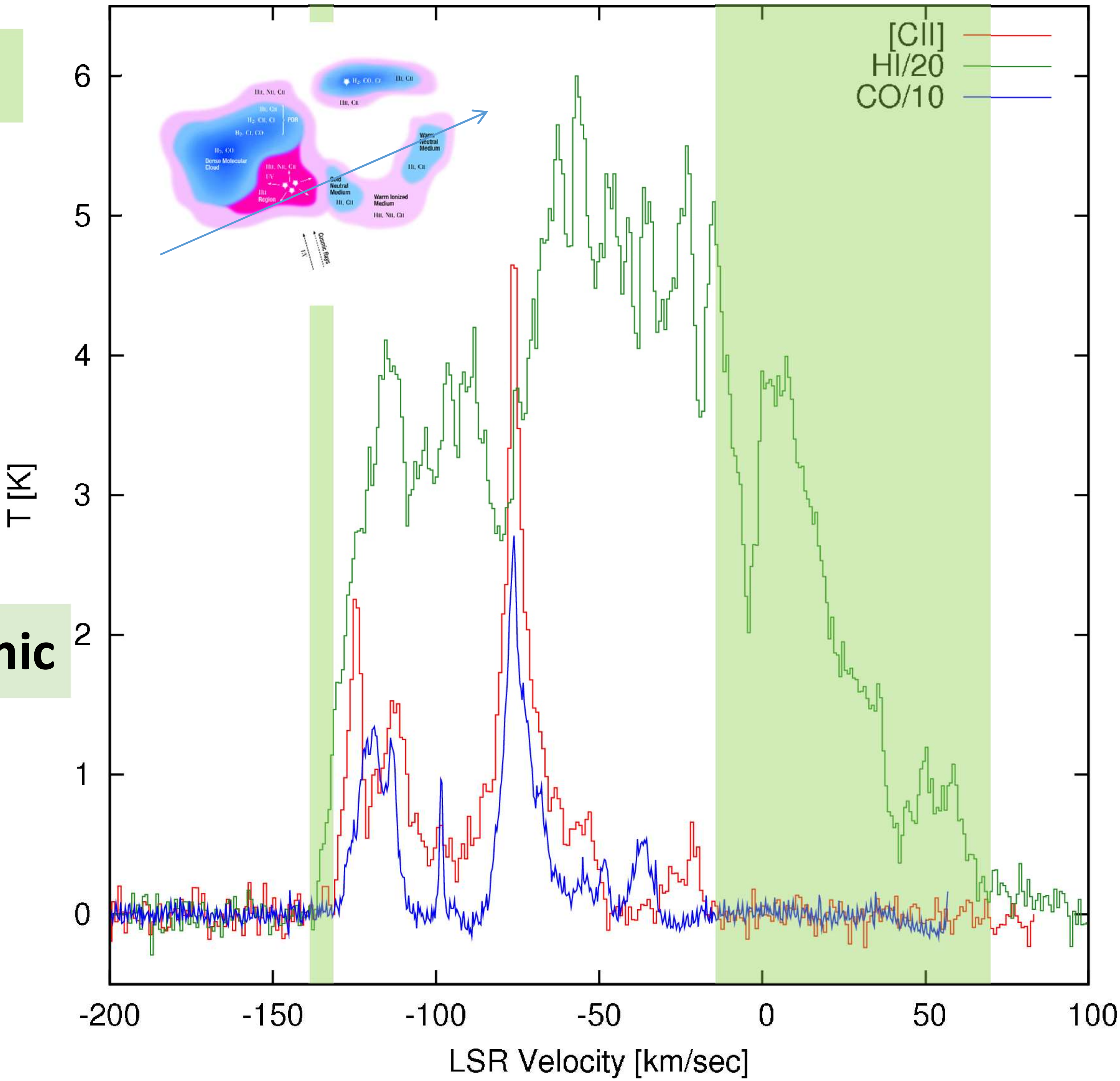
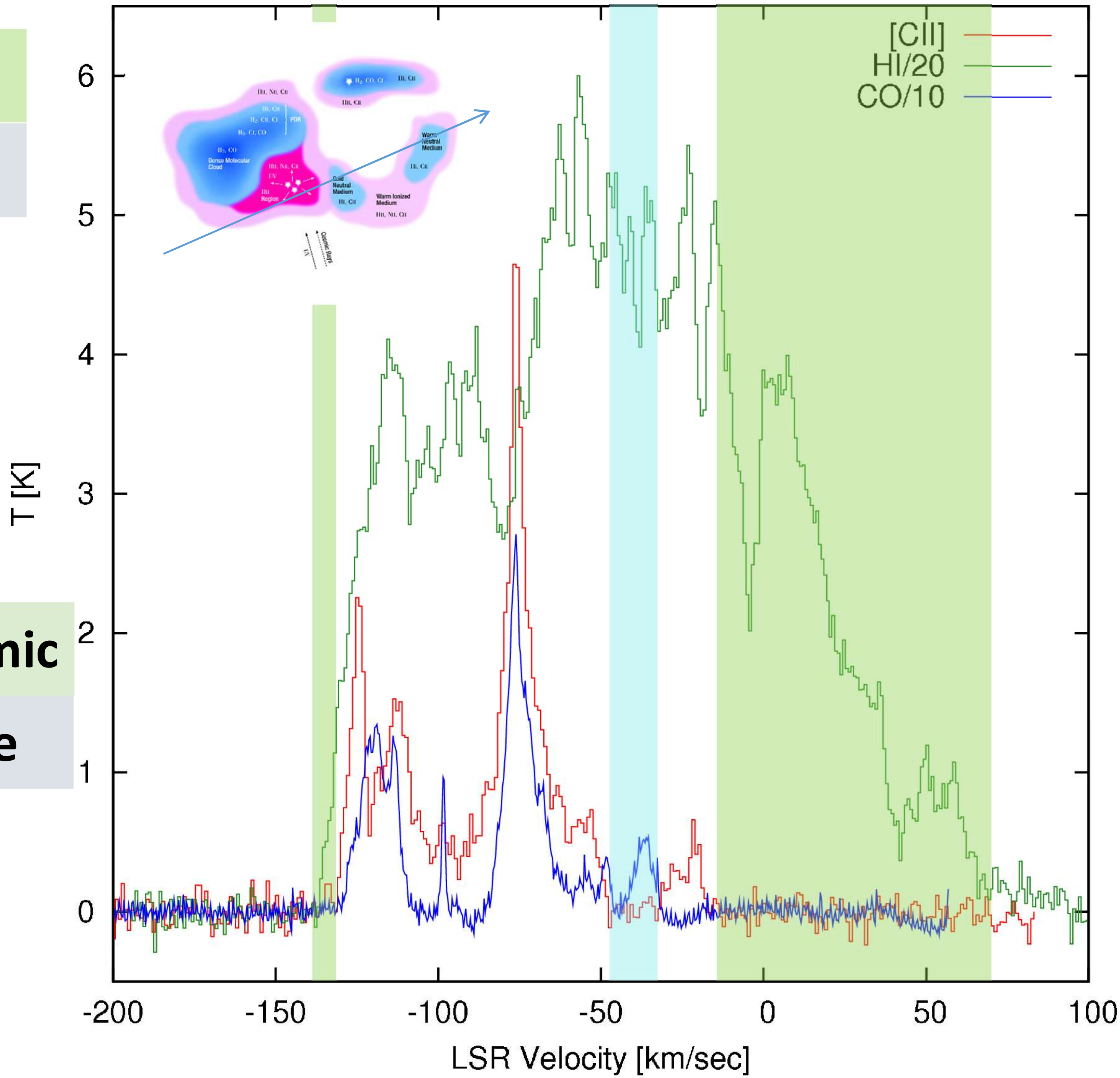
HI



Diffuse Atomic

HI

HI+CO



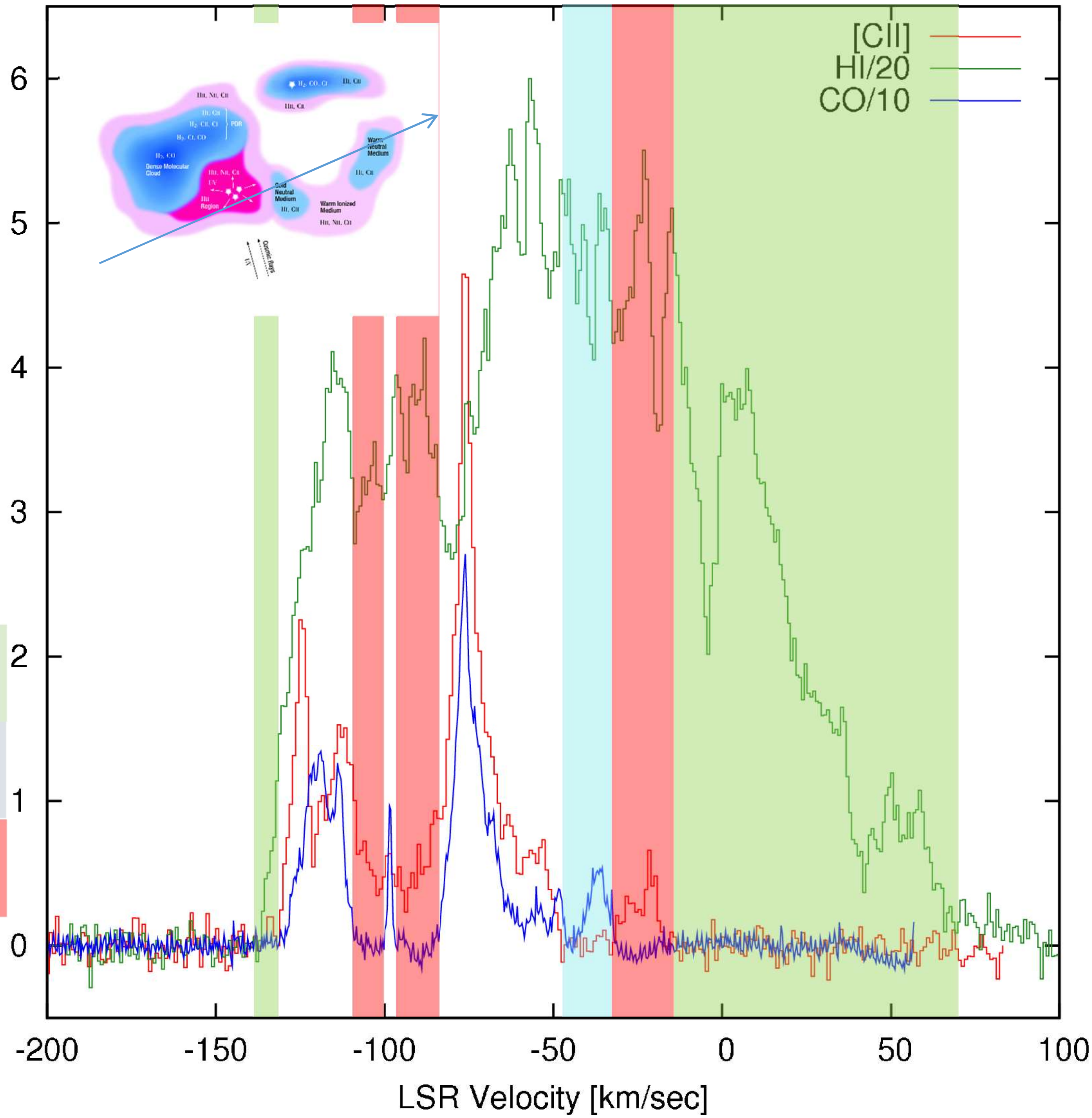
Diffuse Atomic

Cold Dense

HI

HI+CO

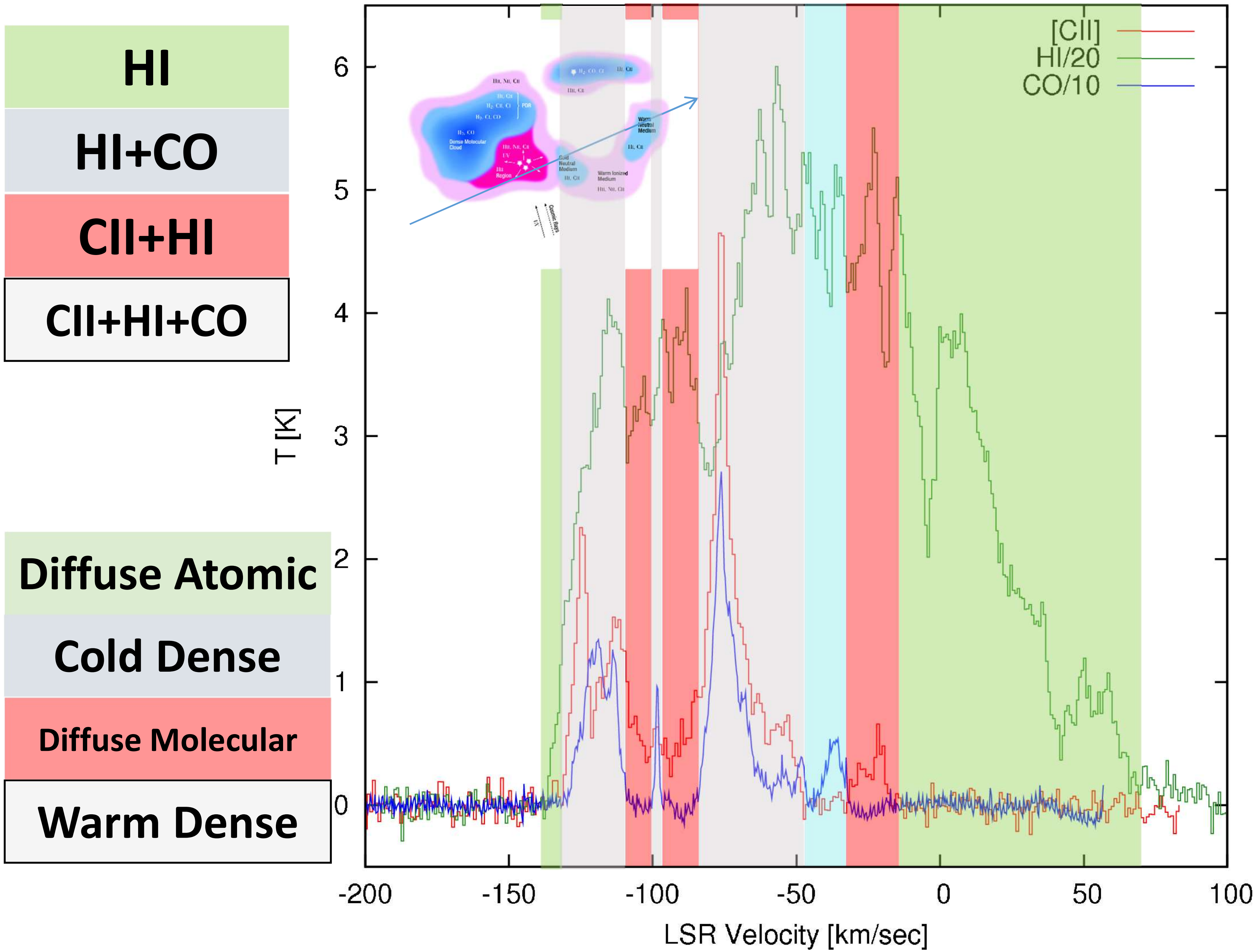
CII+HI



Diffuse Atomic

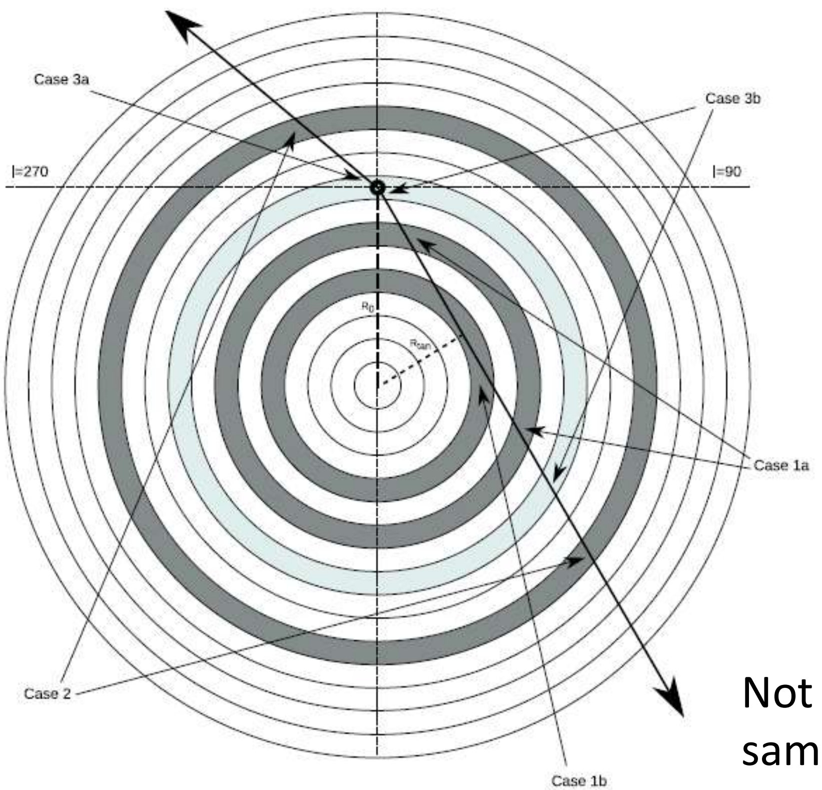
Cold Dense

Diffuse Molecular

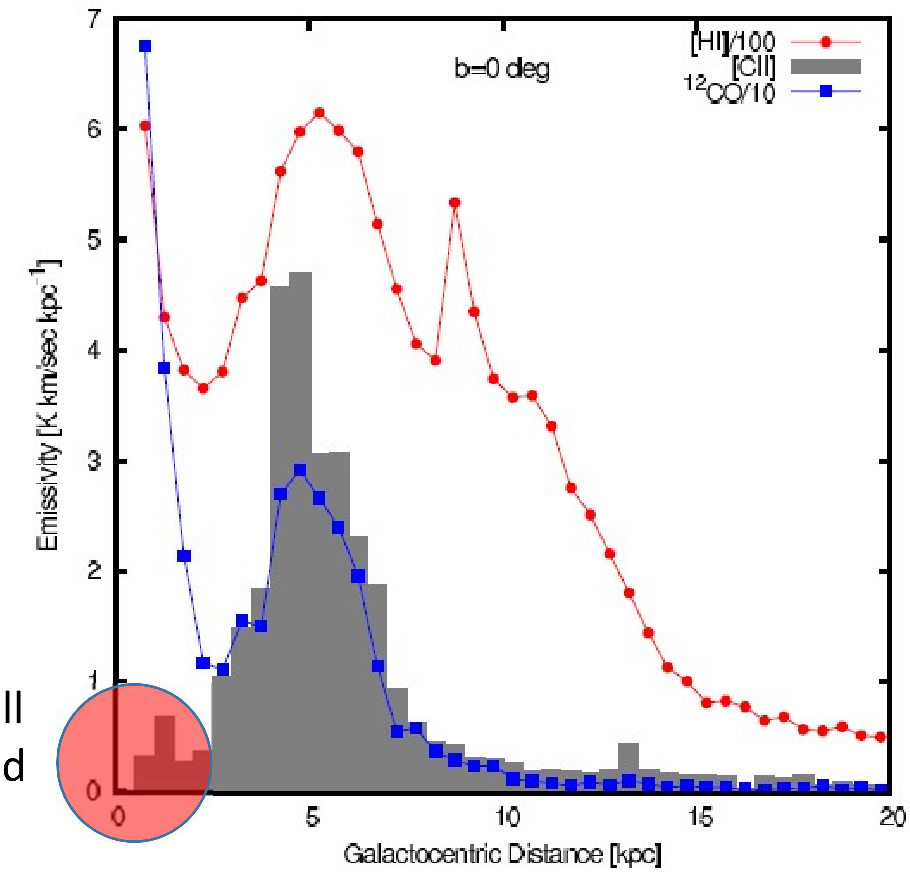

HI
HI+CO
CII+HI
CII+HI+CO
Diffuse Atomic
Cold Dense
Diffuse Molecular
Warm Dense
[CII]
HI/20
CO/10
T [K]
LSR Velocity [km/sec]
-200
-150
-100
-50
0
50
100
0
1
2
3
4
5
6

Galactocentric Distribution

To derive global properties of population of [CII]-emitting clouds in the Milky Way we divide it into a set of rings and calculate the radially average distribution of [CII].



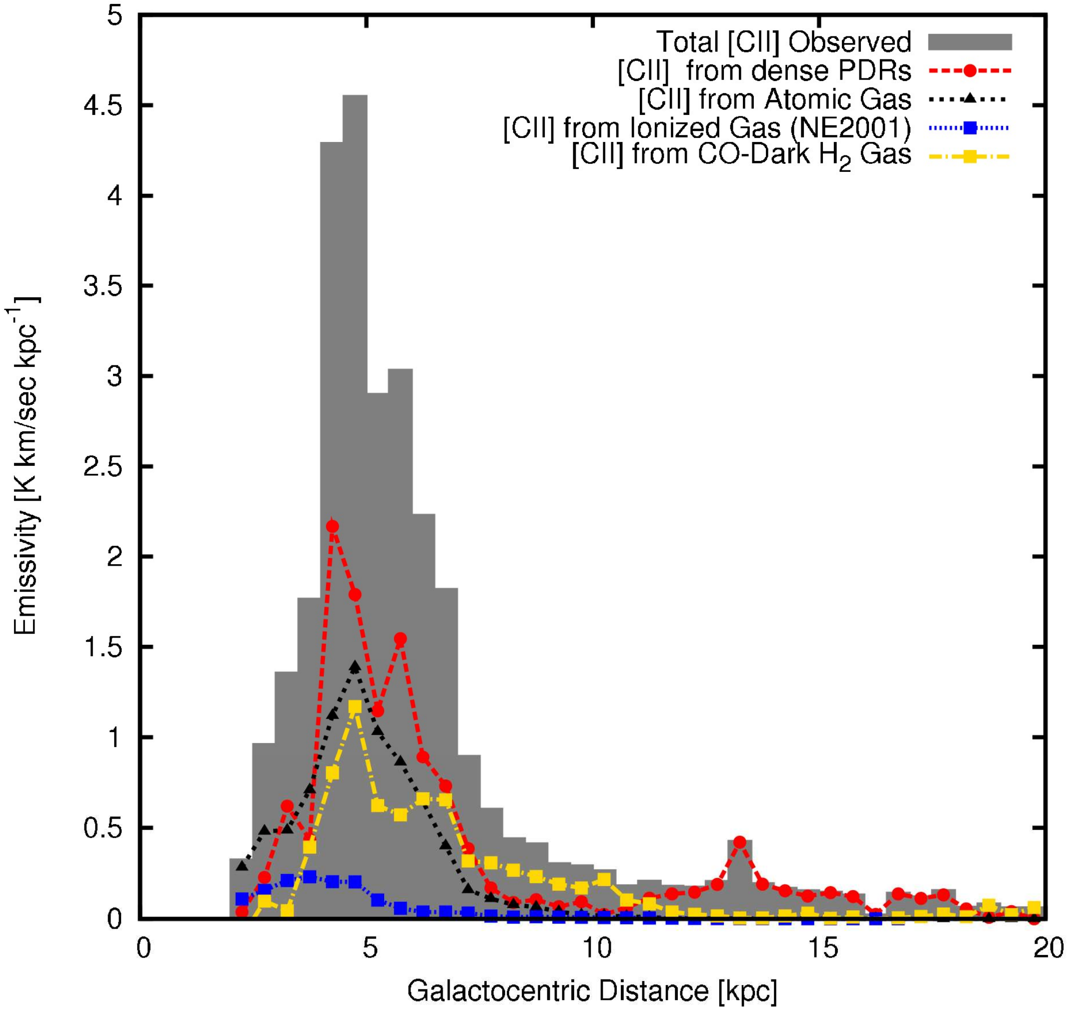
Not well sampled



Most of the [CII] emission in the galaxy comes from the inner galaxy (3-10 kpc). (We are 8.5 kpc away from the galactic center)

The origin of the [CII] emission in the Milky Way

- **PDRs**: [CII] associated with CO and ^{13}CO
- **Atomic Gas**: [CII] contribution from HI assuming two-phase ISM thermal pressure (**Wolfire et al 2003**).
- **Ionized Gas**: Assumed electron density distribution from NE2001.
- **CO-dark H_2 Gas**: [CII] clouds with no CO emission.



Pineda et al. 2013 A&A 554, A103

The origin of the [CII] emission in the Milky Way

Luminosity: emissivity integrated over the volume of the galaxy.

Different components of the [CII] emission in the galaxy occupy different volumes in the galaxy.

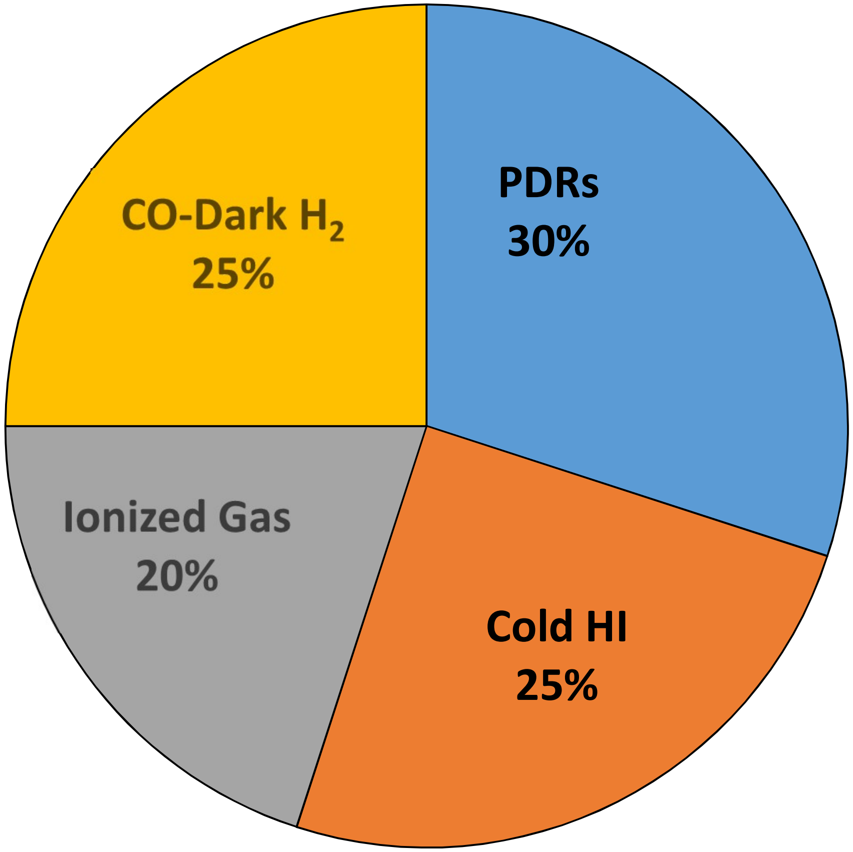
Total [CII] Luminosity of MW: **10^{40} erg/sec**

FWHM (PDRs) = 130 pc (Sanders et al. 1984)

FWHM (CNM, CO-Dark H_2)=172 pc (Langer et al. 2014)

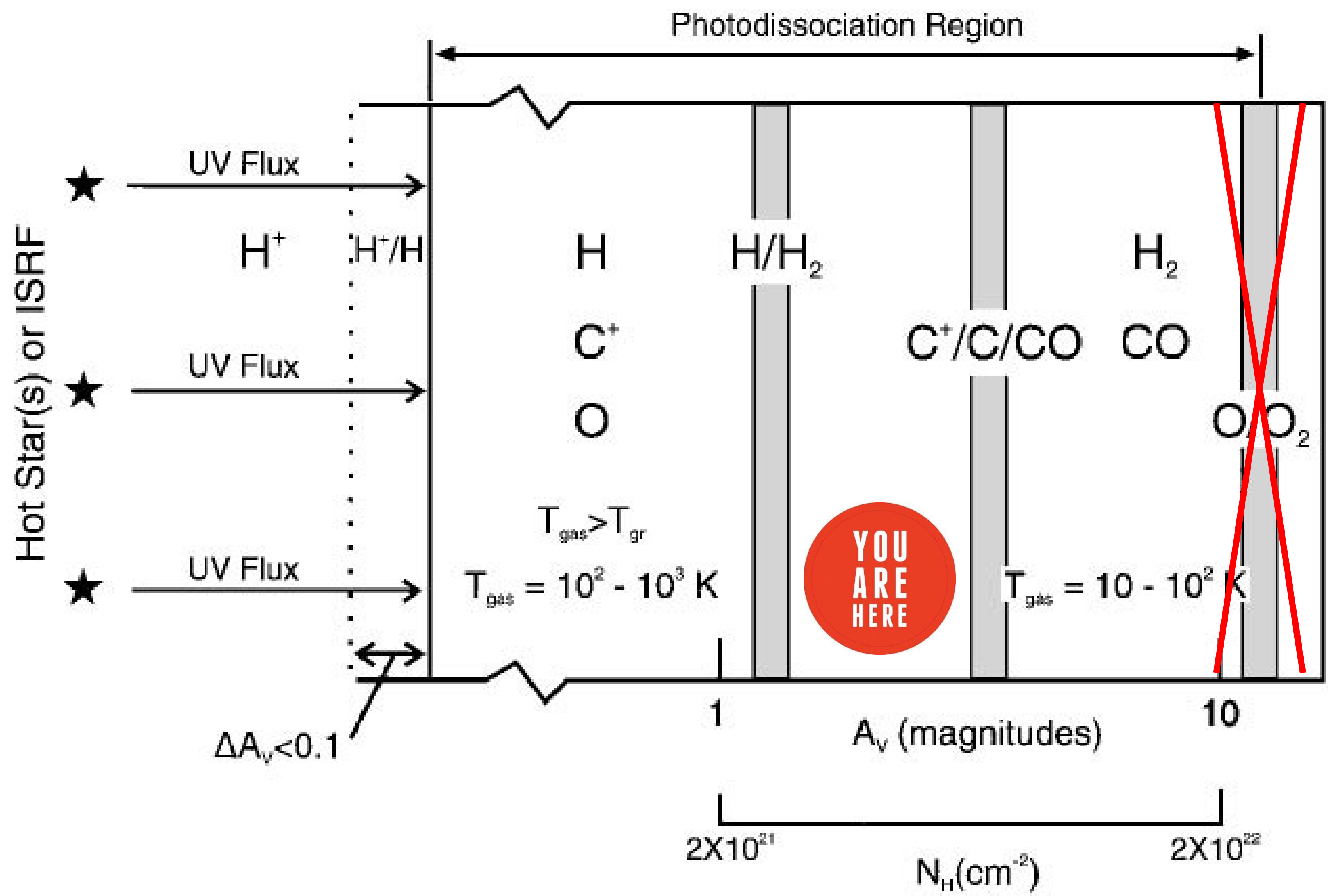
FWHM (ELDWIM) = 1000 pc (Kulkarni & Heiles 1987)

[CII] Luminosity



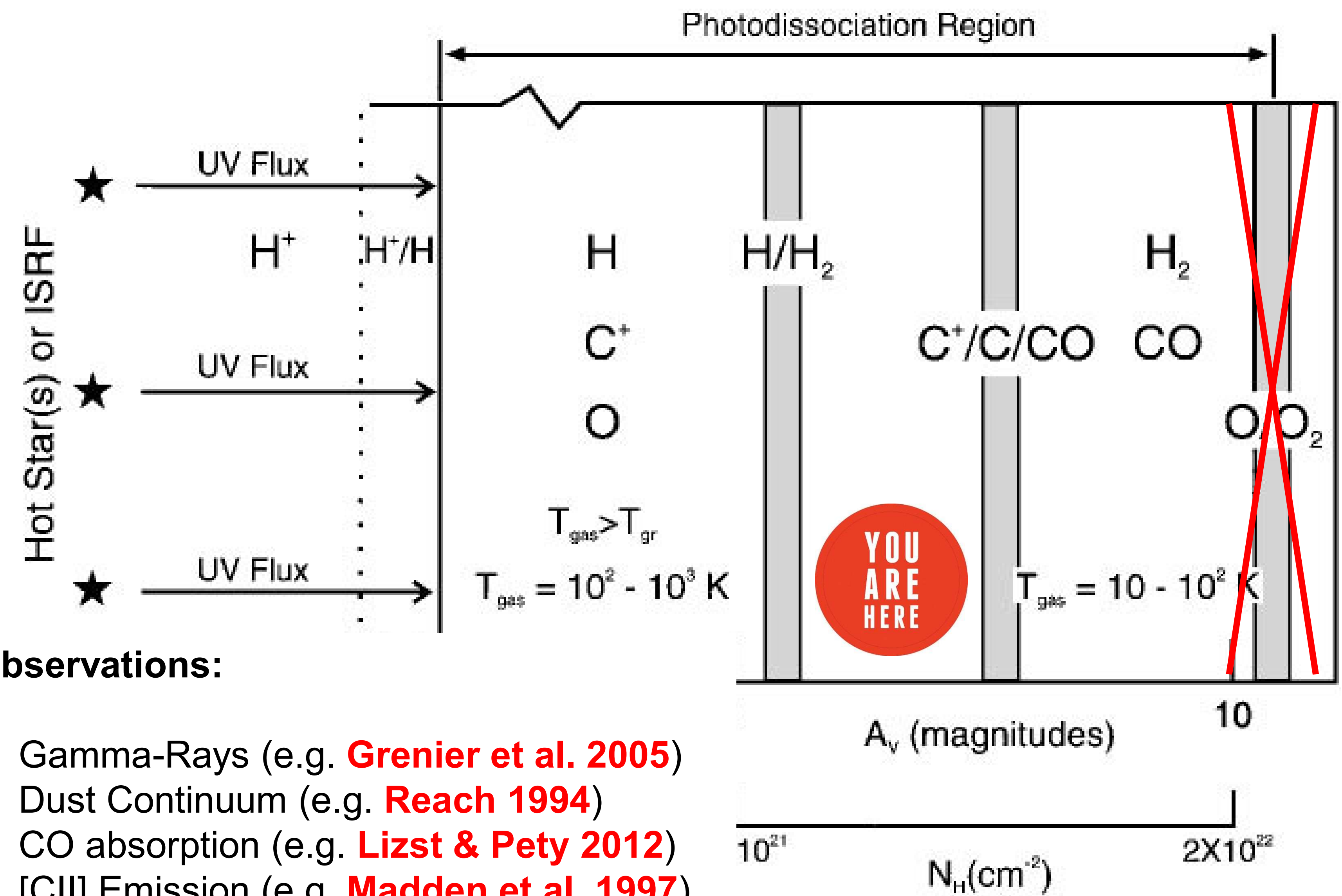
Pineda et al. 2014 A&A 570, A121

CO-“Dark” H_2 Gas



Hollenbach and Tielens (1997)

CO-“Dark” H_2 Gas

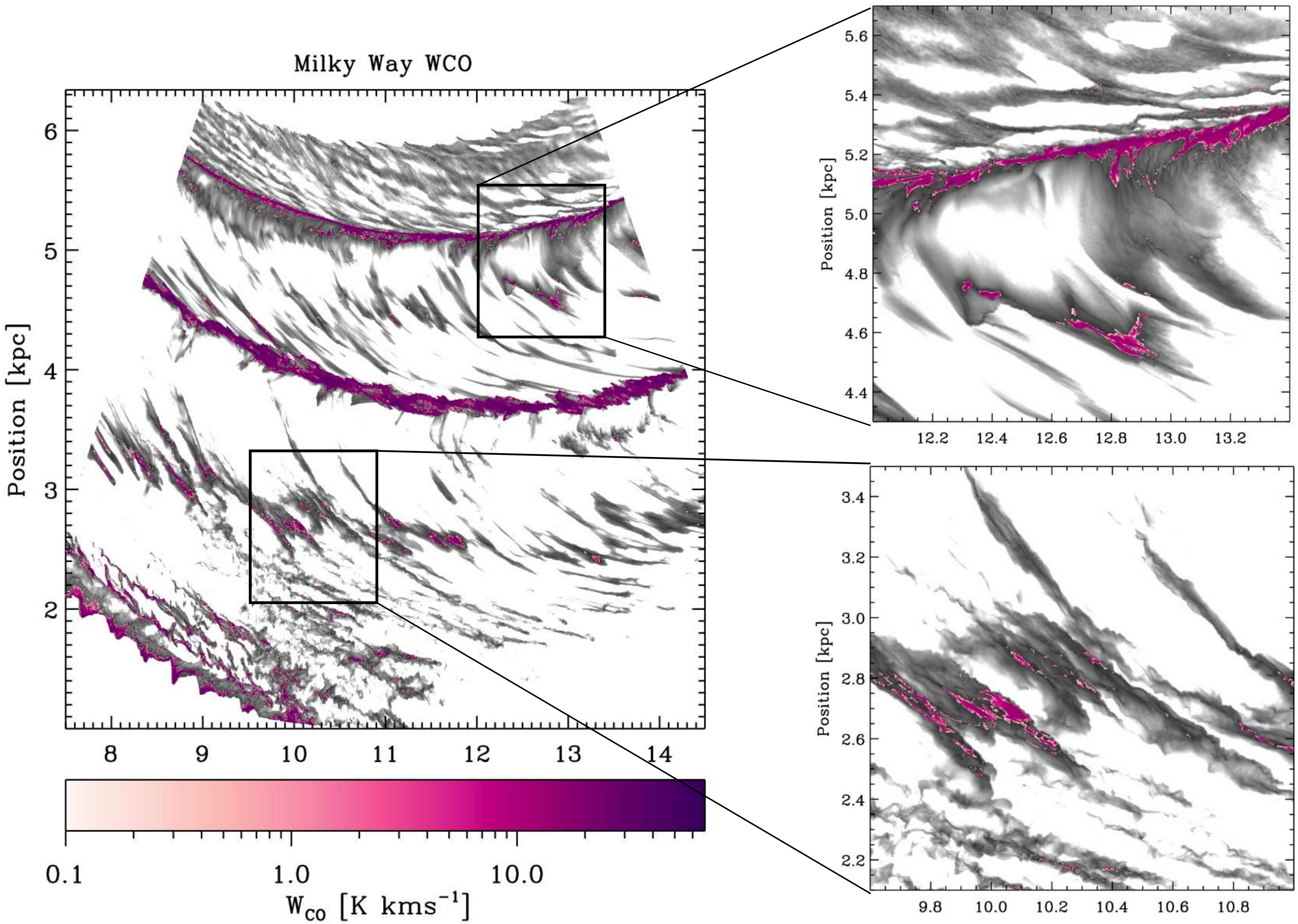


Hollenbach and Tielens (1997)

Observations:

- Gamma-Rays (e.g. **Grenier et al. 2005**)
- Dust Continuum (e.g. **Reach 1994**)
- CO absorption (e.g. **Lizst & Pety 2012**)
- [CII] Emission (e.g. **Madden et al. 1997**)

Smith et al. 2014



The distribution of the CO-dark H_2 gas in the Milky Way

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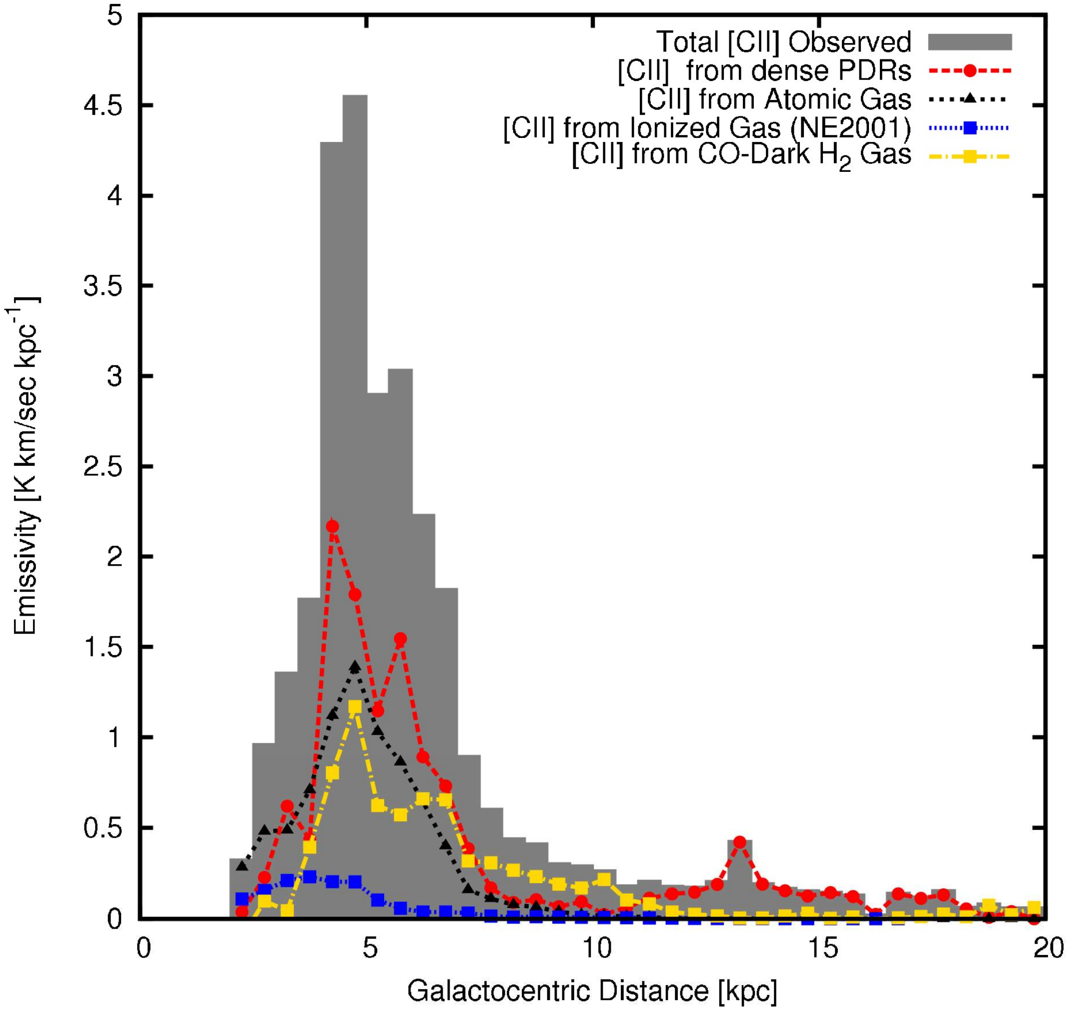


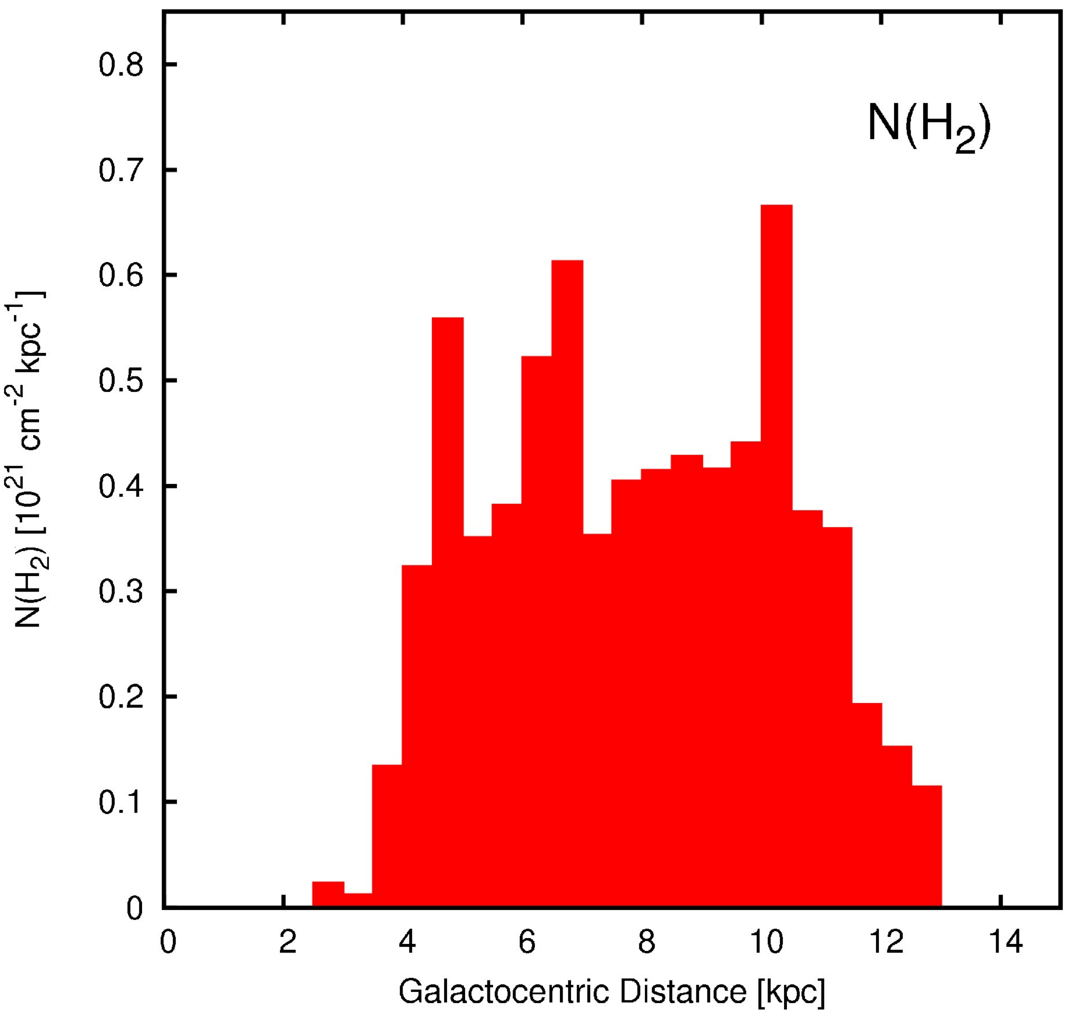
Pineda et al. 2013 A&A 554, A103

The distribution of the CO-dark H_2 gas in the Milky Way

- **[CII] emission is related to N(C+), T_{kin}, and the H_2 volume density.**

- **We assume the thermal pressure gradient from Wolfire et al. 2003.**

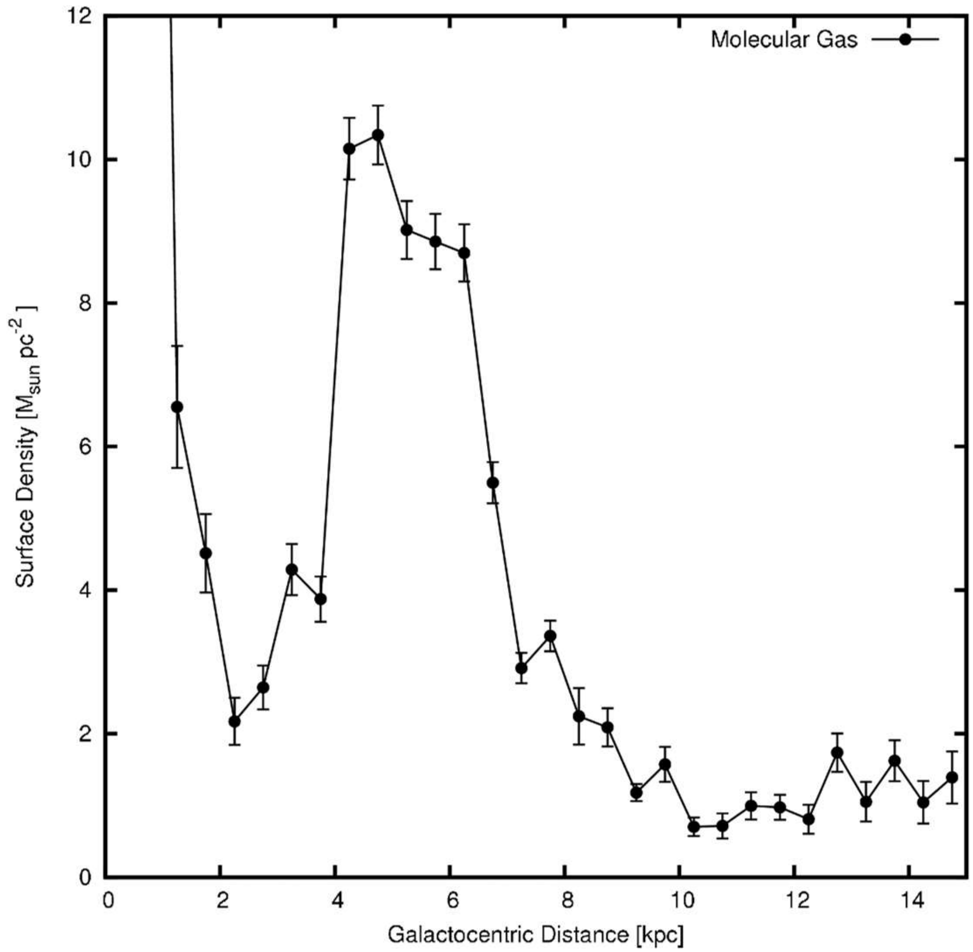
- **We apply the Galactic metallicity gradient from Rolleston et al. 2000.**



Pineda et al. 2013 A&A 554, A103

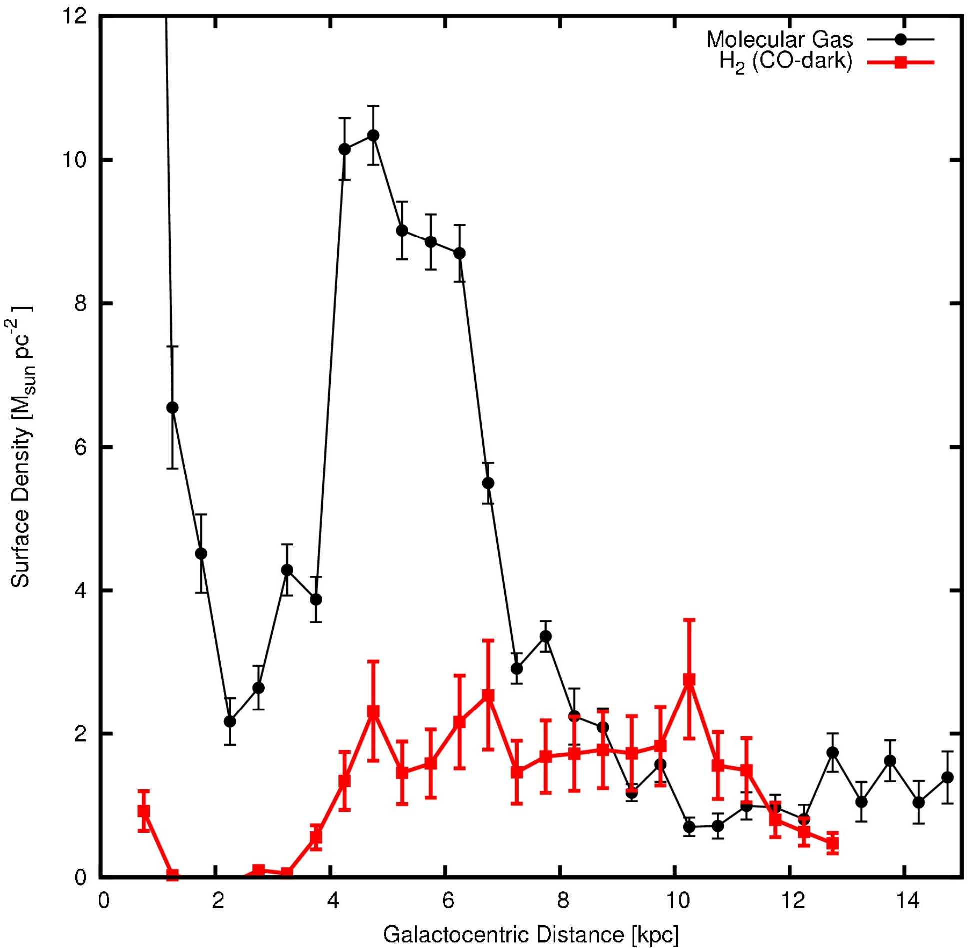
The distribution of the CO-dark H_2 gas in the Milky Way

- The known molecular gas (traced by CO and ^{13}CO) in the Milky Way is concentrated between 3 to 8 kpc from the galactic center.



The distribution of the CO-dark H_2 gas in the Milky Way

- The known molecular gas (traced by CO and ^{13}CO) in the Milky Way is concentrated between 3 to 8 kpc from the galactic center.
- The CO-dark H_2 gas extends to larger distances from the galactic center.
- On average, CO-dark H_2 represents about 30% of the total molecular mass in the Milky Way.

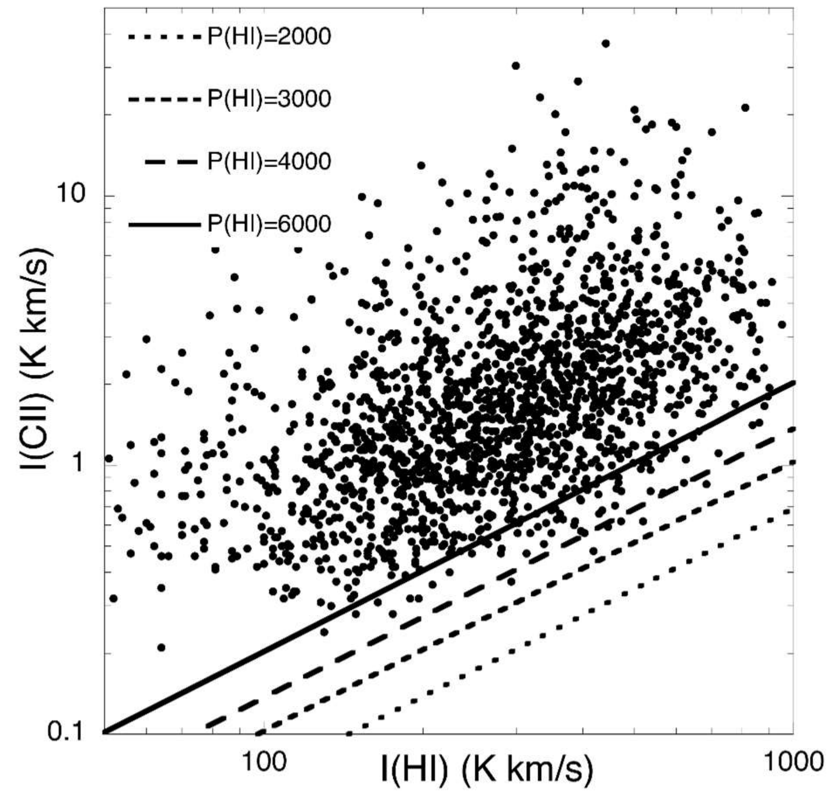


CO-Dark H2 : Individual cloud statistics

Gaussian decomposition of components along the LOS. 2000 components identified. HI contribution to [CII] intensity subtracted.

Clouds are separated in four types depending in which tracers are detected

CO-dark H_2 fraction varies for different types of clouds



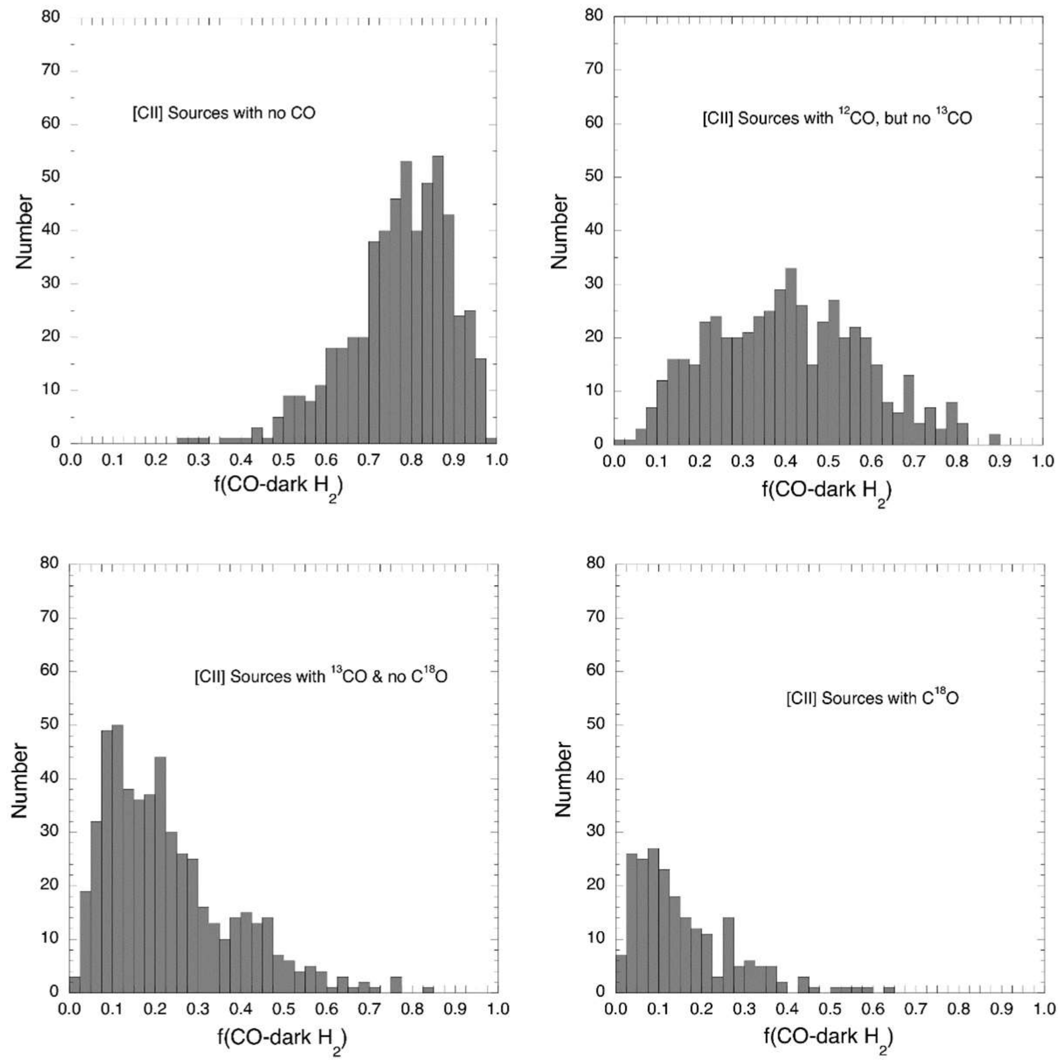
Langer et al. (2013), A&A 562, A122
See also:
Velusamy et al. (2012), IAU Symposium
Langer et al. (2010), A&A. 521, L17
Velusamy et al. (2010), A&A. 521, L18

Observations in "3D": Technique - 2: [CII]

Gaussian decomposition of components along the LOS. 2000 components identified. HI contribution to [CII] intensity subtracted.

Clouds are separated in four types depending in which tracers are detected

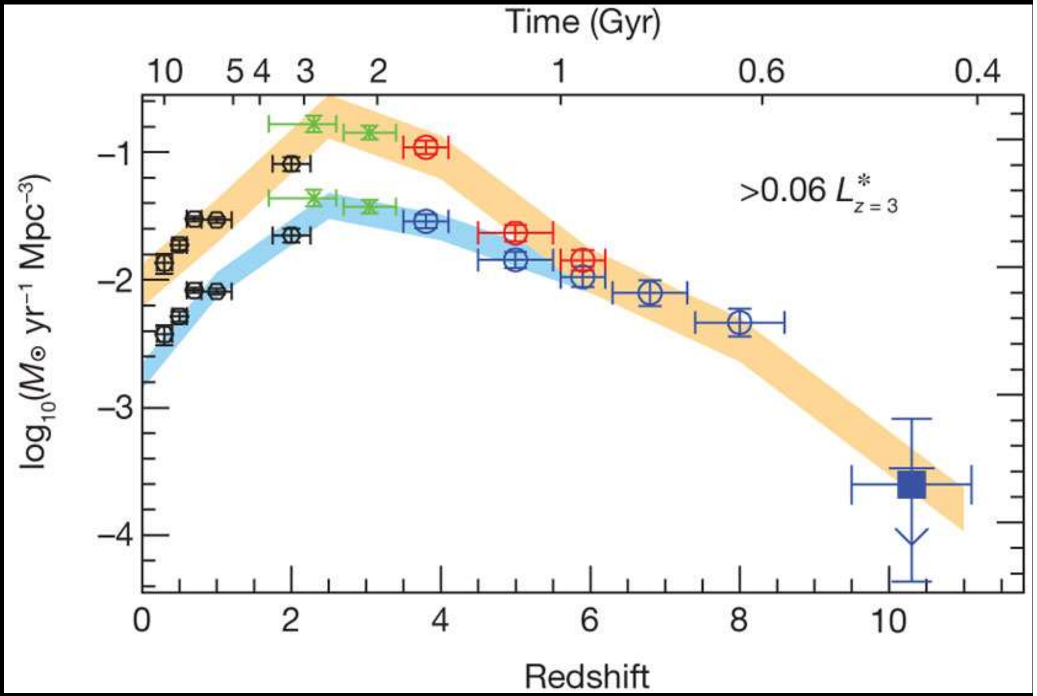
CO-dark H_2 fraction varies for different types of clouds



Langer et al. (2013), A&A. submitted.

The star formation rate

- An important parameter used to characterize star formation in galaxies over cosmic time.
- Measured in units of solar masses per year.
- The peak of star formation in the Universe occurred at redshift Z=2.
- It is important to find tracers of star formation that can be observed in galaxies over a wide range of redshifts.

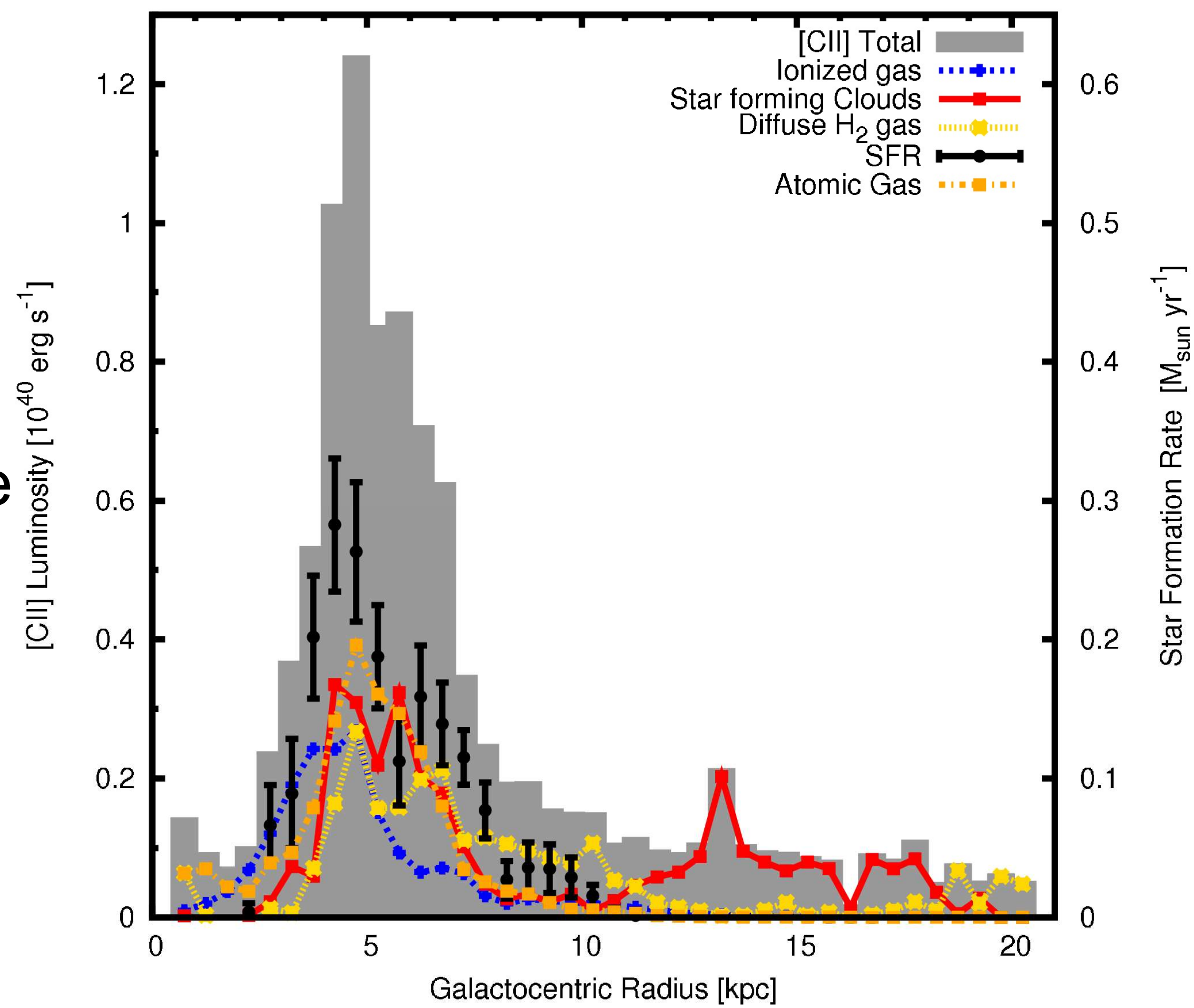


[CII] Luminosity Distribution of the Milky Way

The total energy emitted by the galaxy in [CII]: Luminosity

Intensity integrated over the volume of the galaxy.

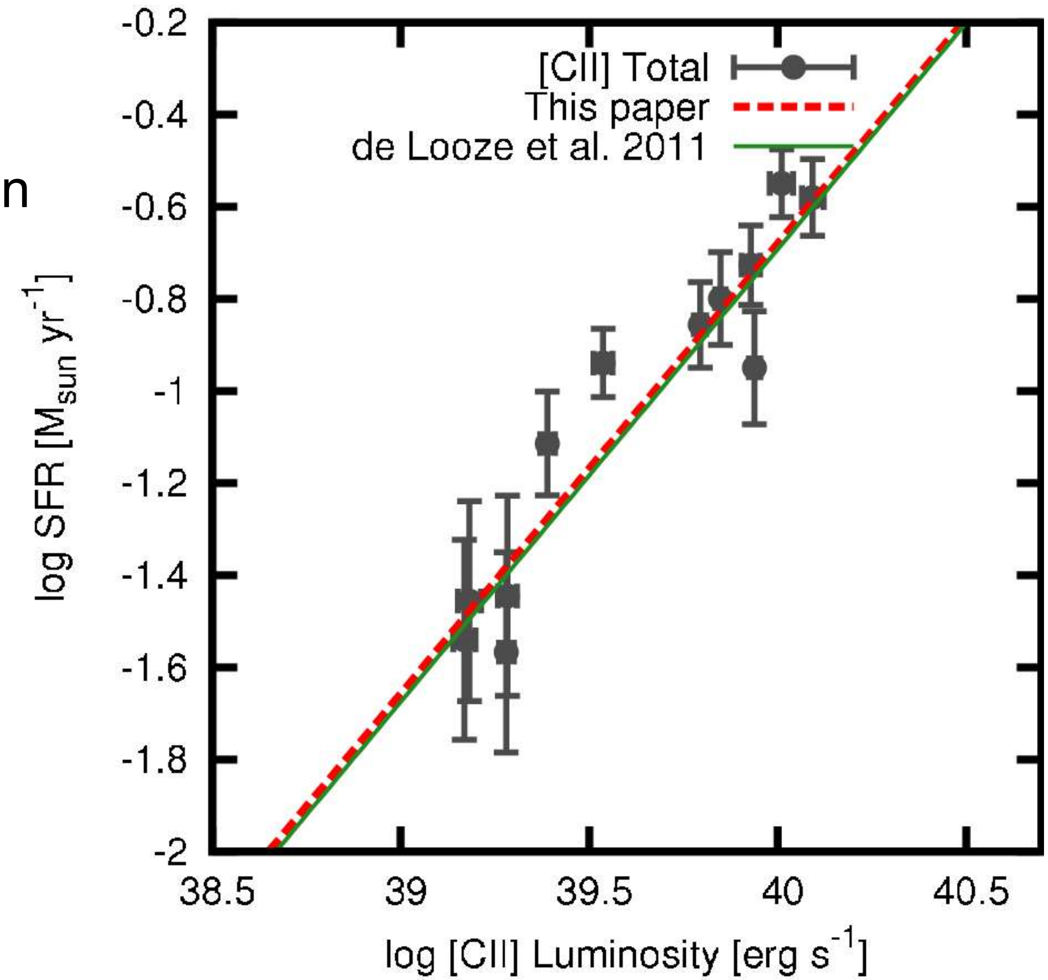
Total [CII] Luminosity of MW: **10^{40} erg/sec**



Pineda et al. 2014 A&A 570, A121

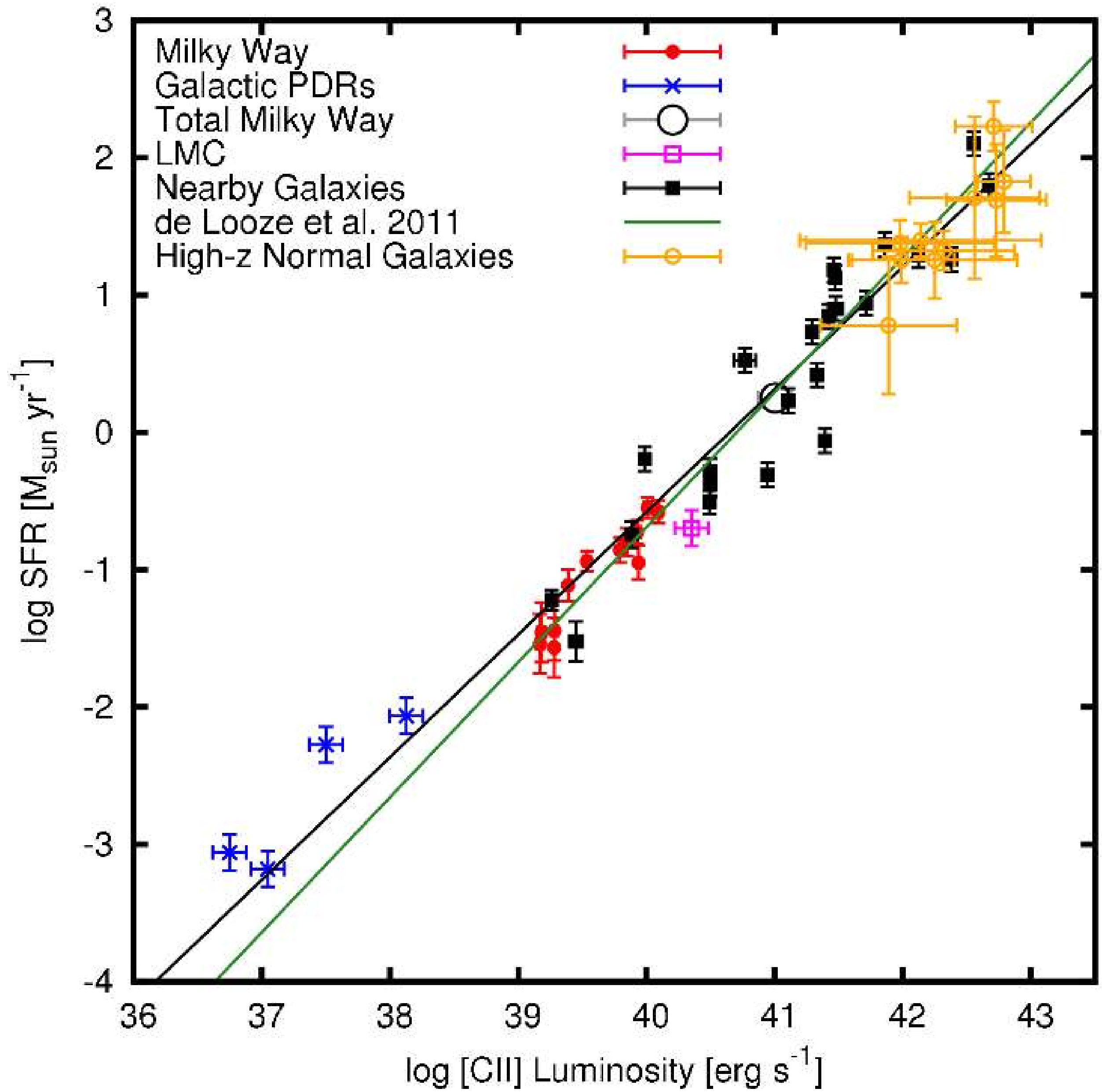
[CII] Luminosity versus the Star Formation Rate in the Milky Way

- The star formation rate is well correlated with the [CII] emission in the plane of the Milky Way.
- In the galactic plane the [CII] luminosity and SFR is close to that found for extra-galactic observations.



[CII] and star formation rate as correlated over 6 orders of magnitudes going from individual clouds to entire galaxies.

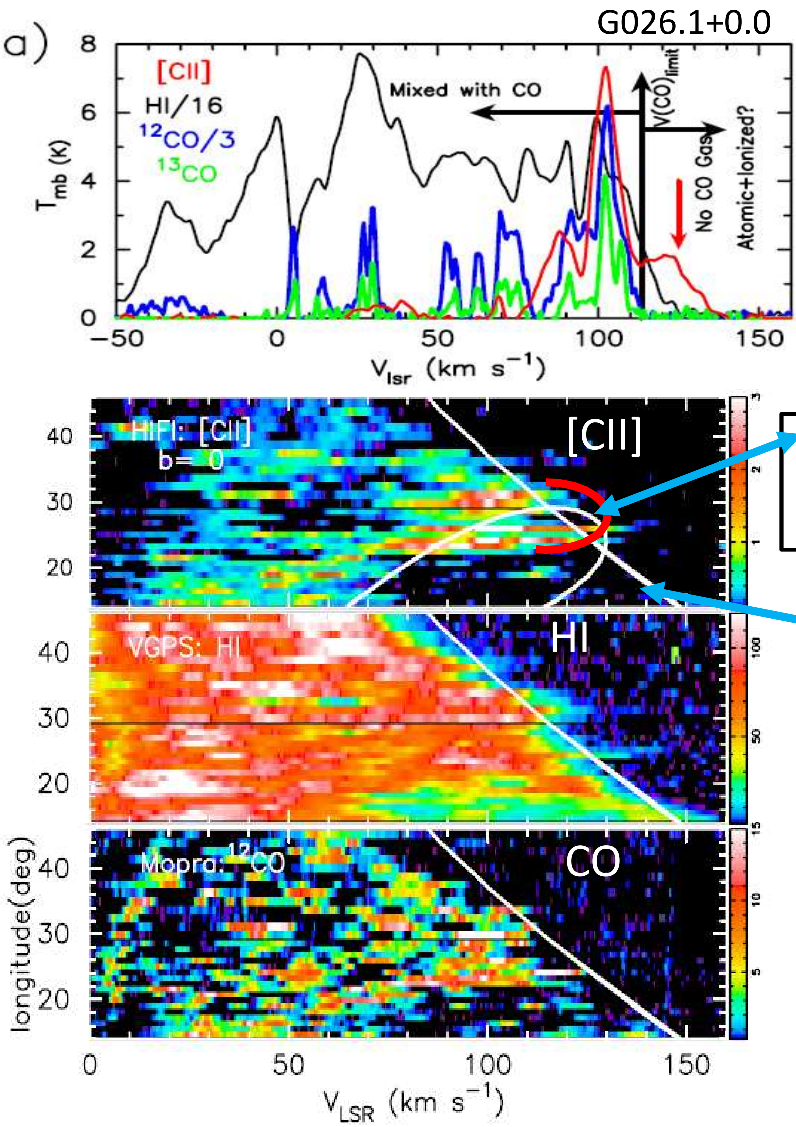
[CII] is a powerful tracer of the star formation rate.



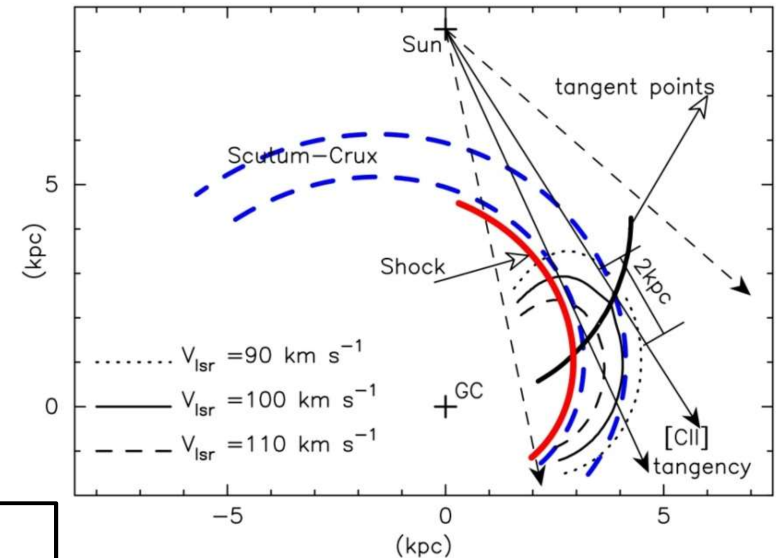
Pineda et al. 2014 A&A 570, A121

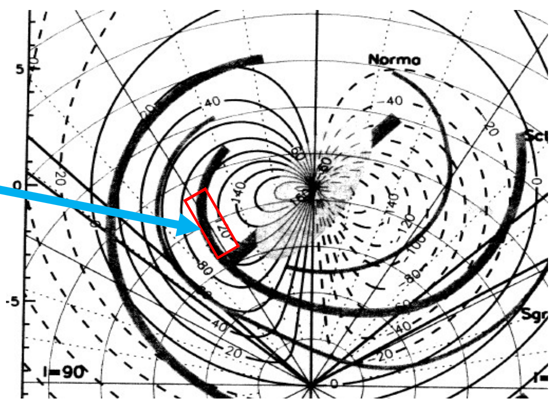
GOT C+ [CII] detection of WIM in Spiral Arm Tangency

Velusamy, Langer et al. 2012, A&A 541,L10



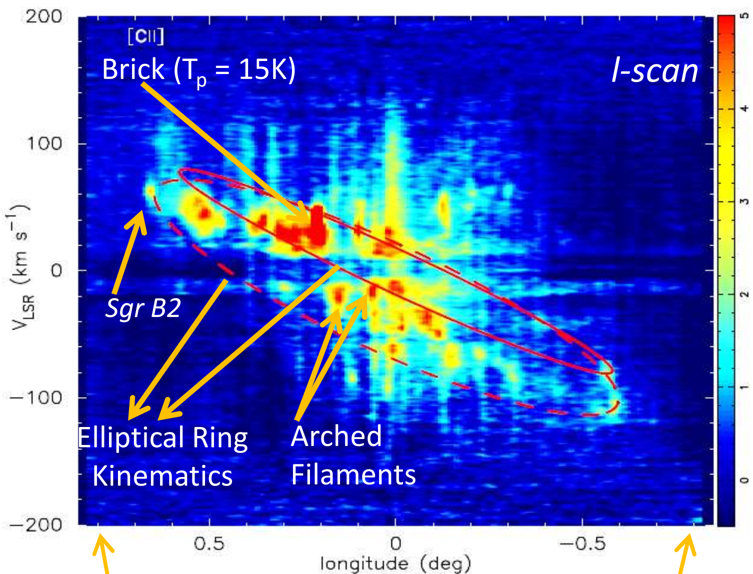
[CII] excess tracing WIM

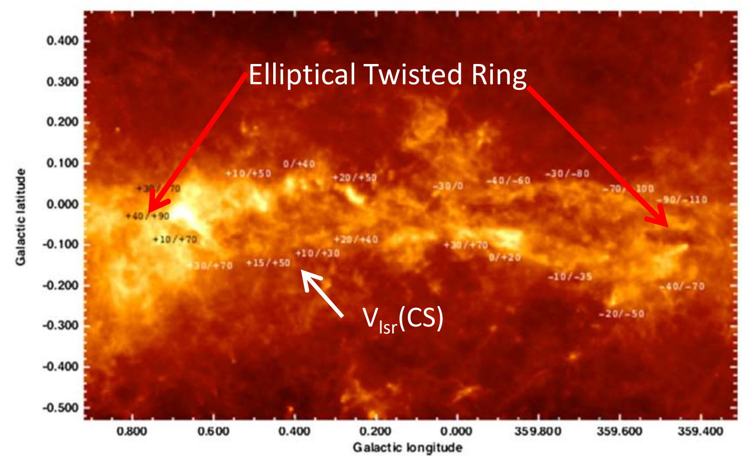




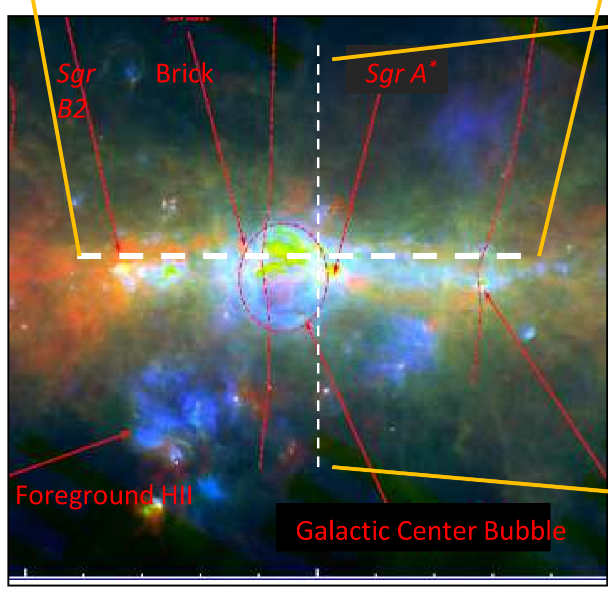
The geometry of the Scutum-Crux (S-C) arm is very favorable to detect weak [CII] emission from the WIM and study its structure and kinematics

Herschel HIFI [C II] OTF Longitude-Latitude Scans (1.6°X1.6°)

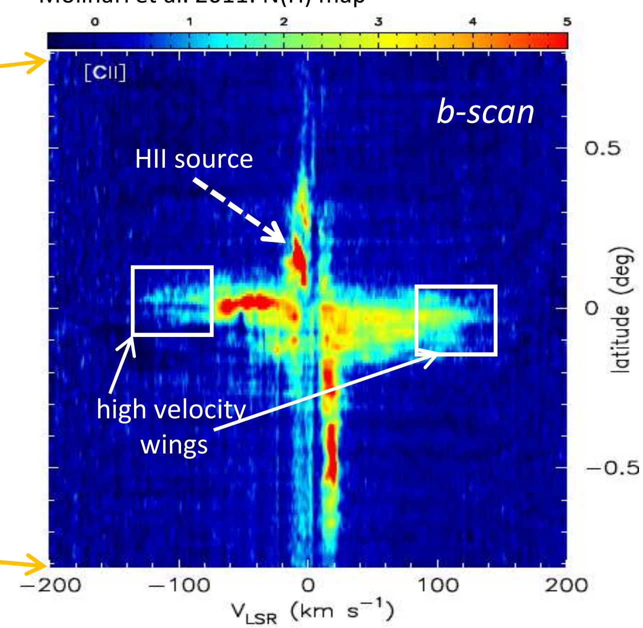




Molinari et al. 2011: N(H) map



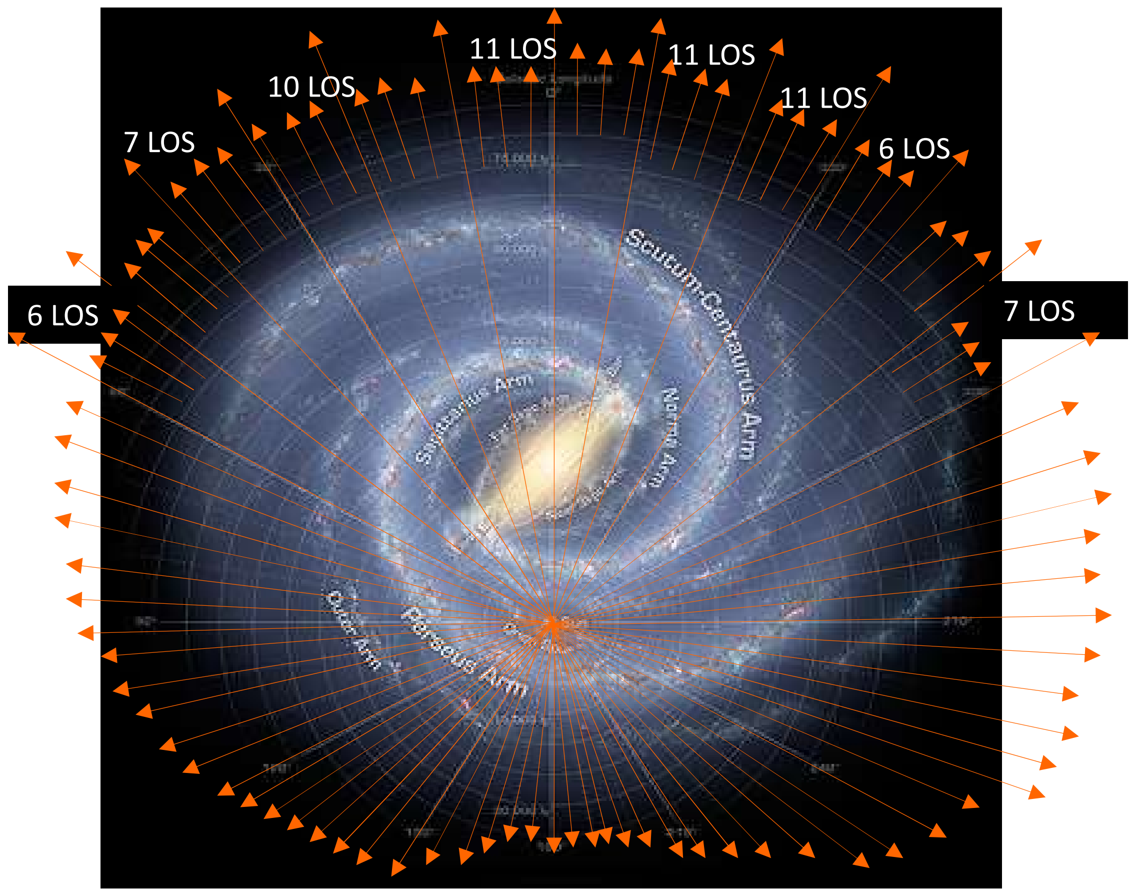
Molinari et al. 2014: Composite 24, 70, 500 µm



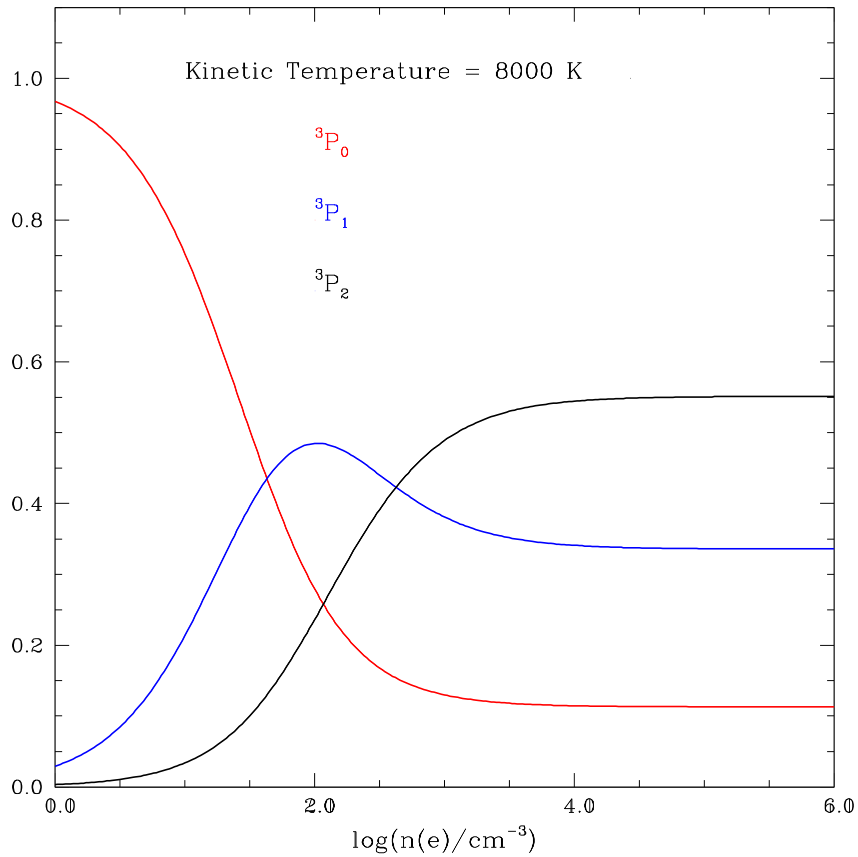
Langer et al. (2017 A&A 599, A136)

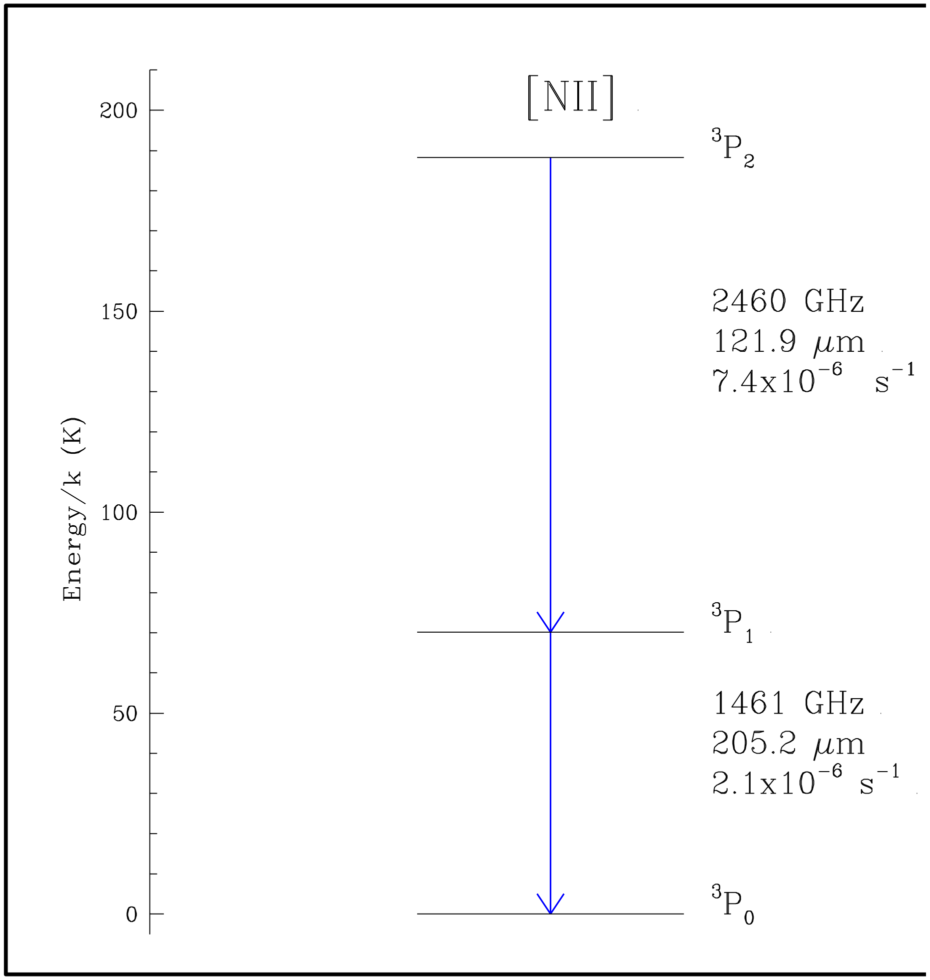
The Herschel [NII] Galactic Plane Survey

- Herschel OT2 Project. PI: Paul Goldsmith
- 140 GOT C^+ lines of sight at $b=0^o$ observed in [NII] 205 um and 122um with PACS (897 s per observation)
- 10 selected lines of sight in [NII] 205um with HIFI (7041 s per observation)



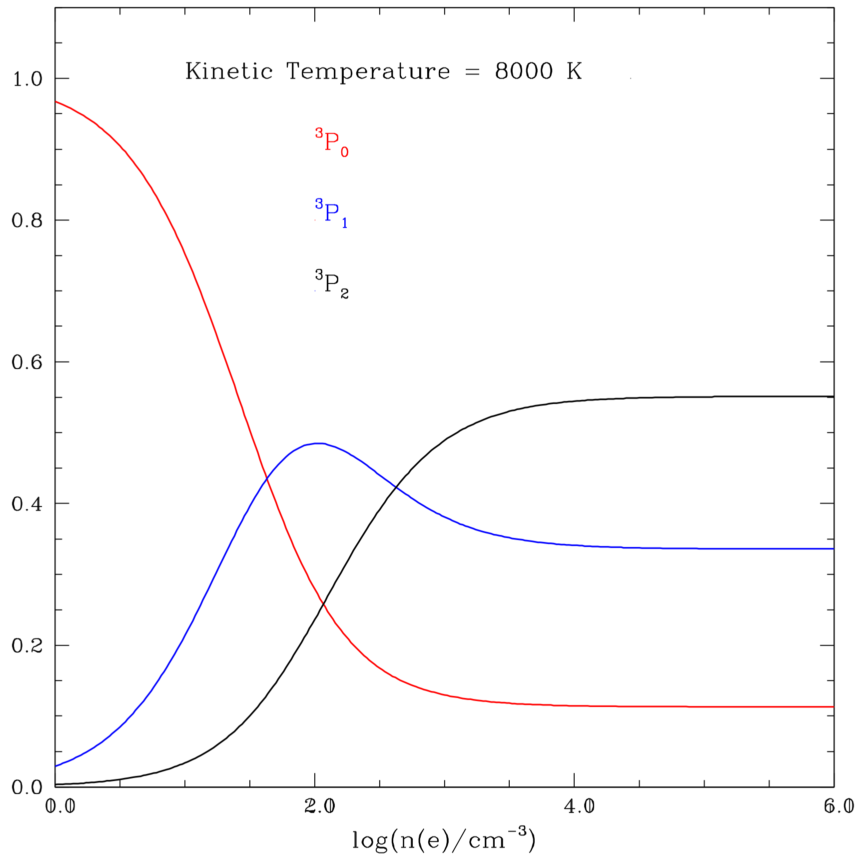
Collisional Excitation of N^+ Fine Structure Line Emission



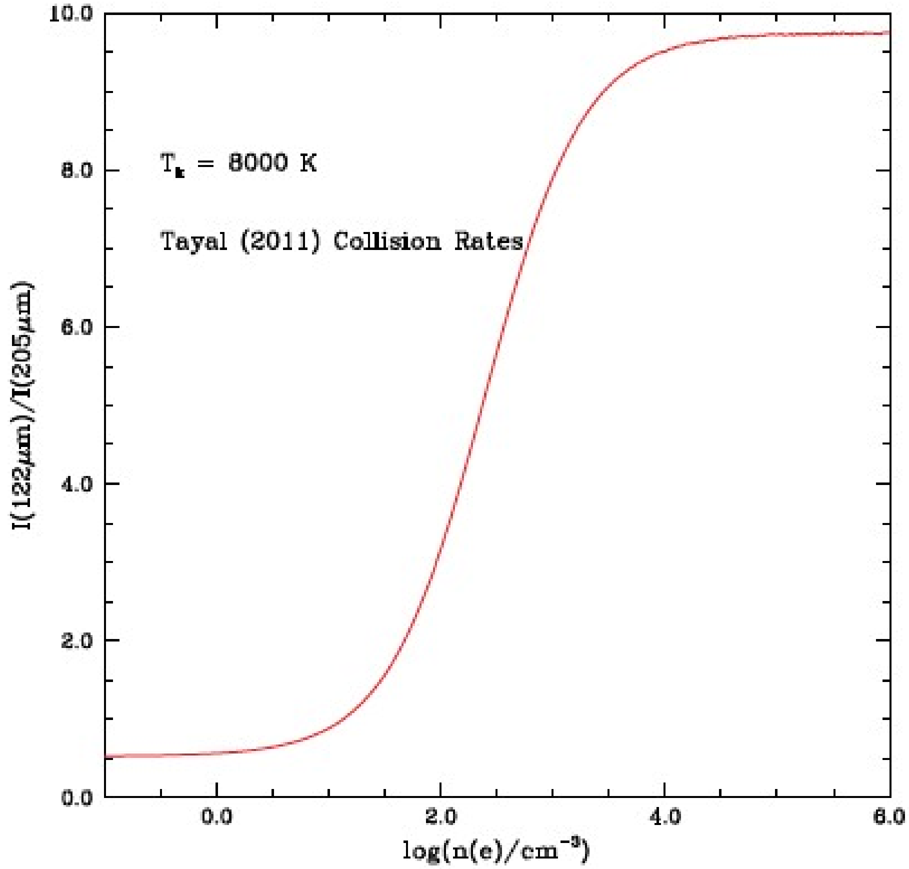


For low densities, most of population is in the ground state and hence detectable ONLY in absorption

Collisional Excitation of N^+ Fine Structure Line Emission

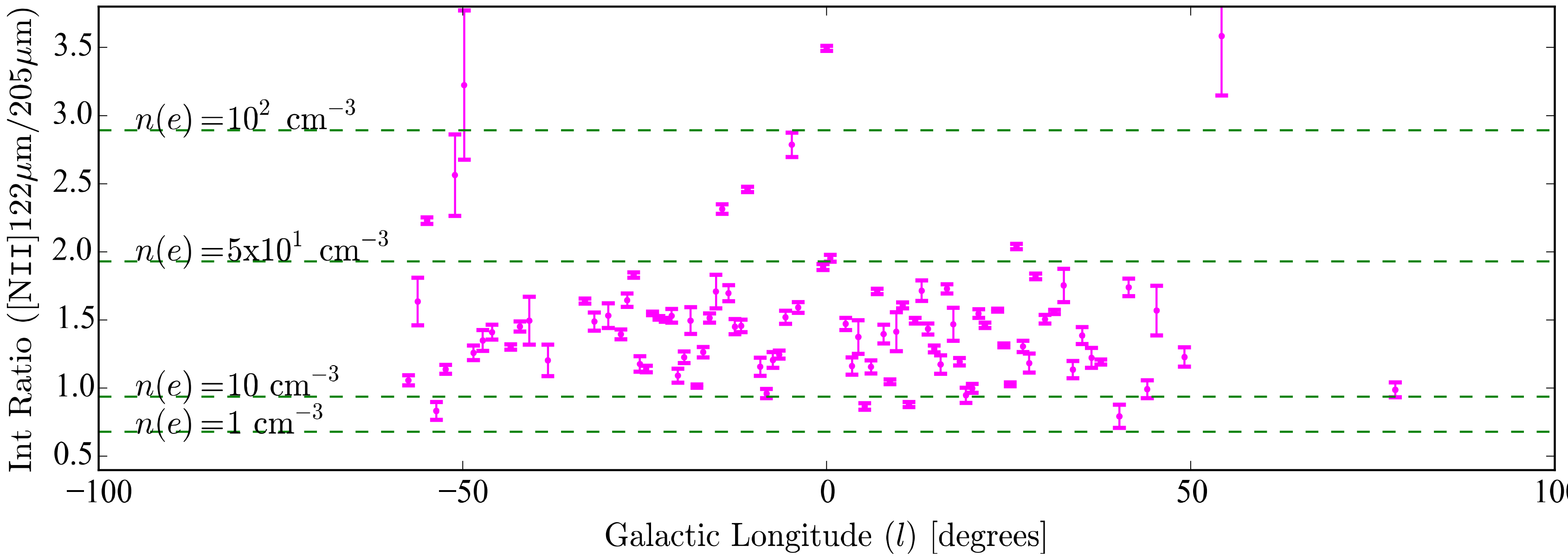


For low densities, most of population is in the ground state and hence detectable ONLY in absorption



For a single density along LOS n(e) determines **I(122)/I(205)** and vice-versa

Electron density distribution as a function of Galactic longitude (from [NII] 122um/205um)

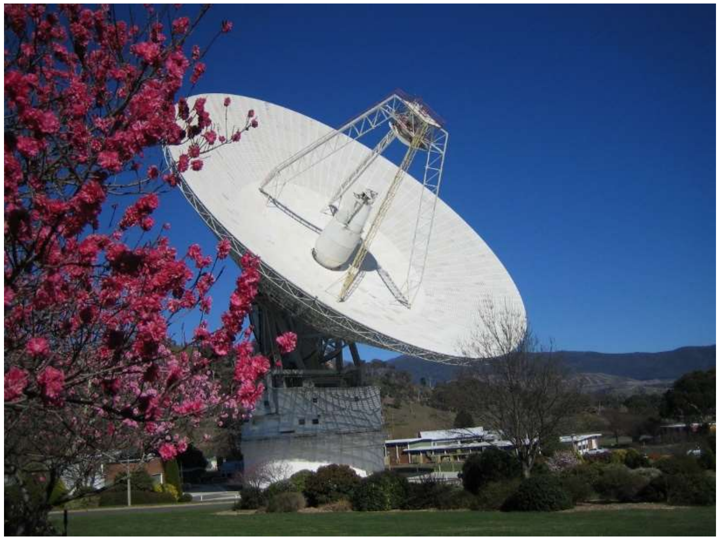


Goldsmith, Yildiz, Langer and Pineda (2015) ApJ

- The [NII] 122um/205um gives the electron density.
- Typical n_e =10 – 50 cm^{-3}. Much larger than WIM (~0.1 cm^{-3}).
- Is the density the average along the line of sight? Or is dominated by a single source? **We need a velocity resolved, unobscured tracer of ionized gas.**

Radio Recombination Line Survey of the Galactic Plane

- Hydrogen recombination lines tracers of the same highly ionized gas traced by [NII].
- We are observing 112 GOT C+ lines-of-sight in RRL with the NASA DSS-43 70m telescope in K and X bands.
- Several RRLs in the band allow us to stack them, significantly increasing the sensitivity of the observations.
- 110” (X-band) angular, <1 km/sec velocity resolution) with DSS 43.
- 80” (X-band) angular, <1 km/sec velocity resolution) with GBT.

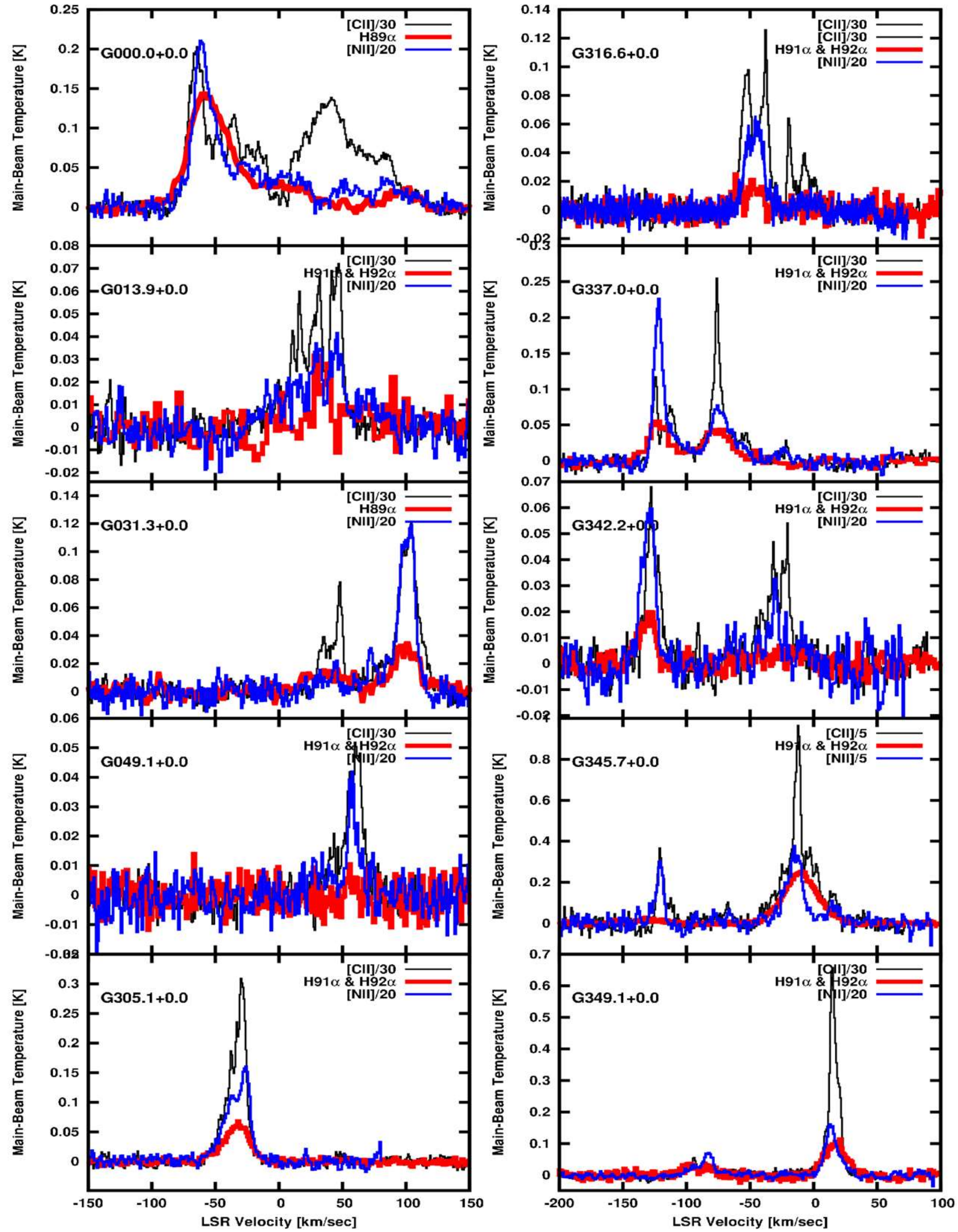


NASA DSS-43 Deep Space Network 70m antenna.
Canberra, Australia.

Green Bank 100m Telecope, West Virginia, USA

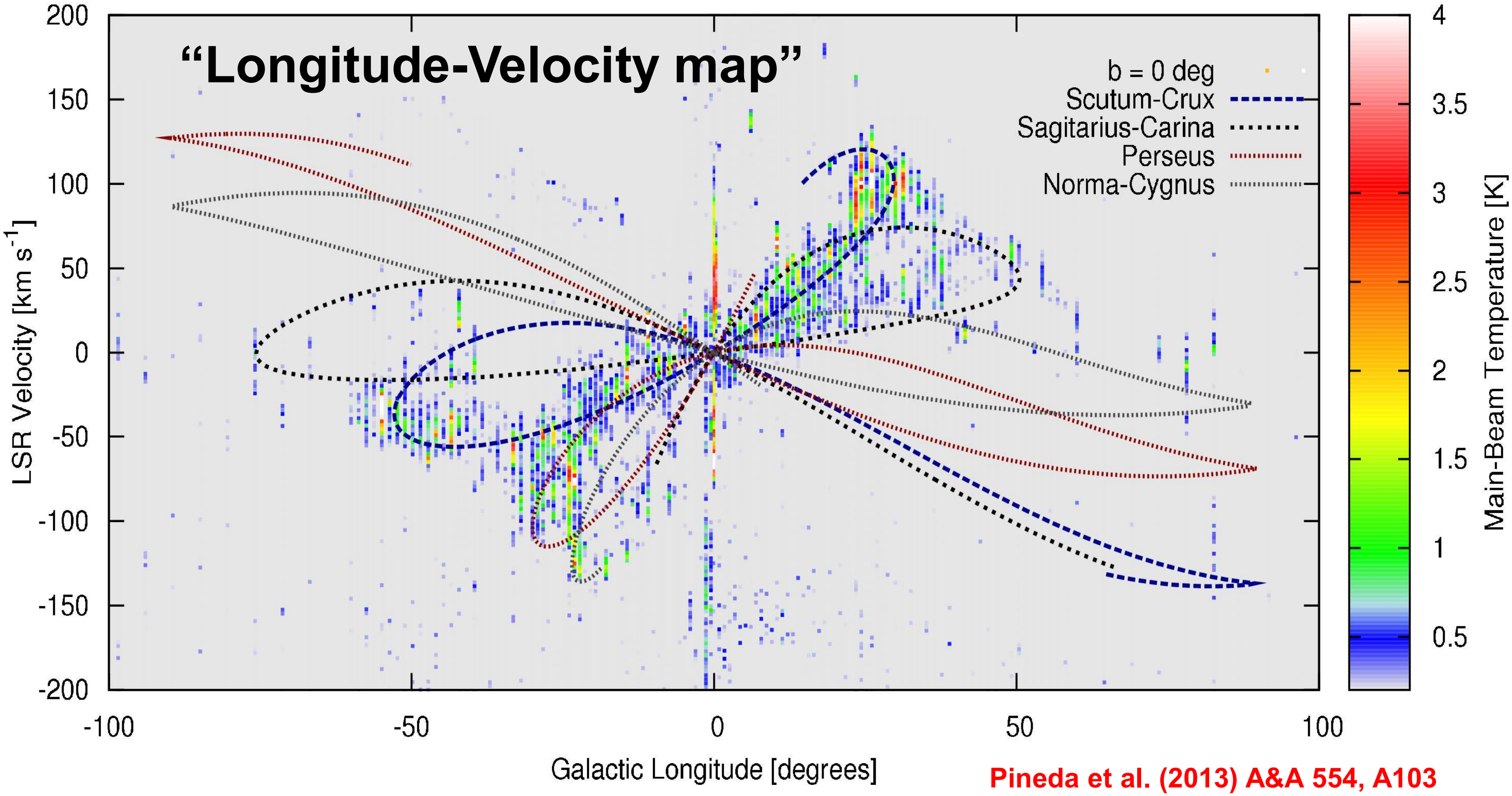
Comparison between RRL, [CII] and [NII] lines in the MW.

- RRL tends to follow [NII] and [CII] emission.
- But [CII]/RRL and [NII]/RRL vary from place to place.
- Wide range of physical conditions in the observed clouds.



Red: H91a and H92a
Blue: [NII] 205um
Black: [CII] 158um

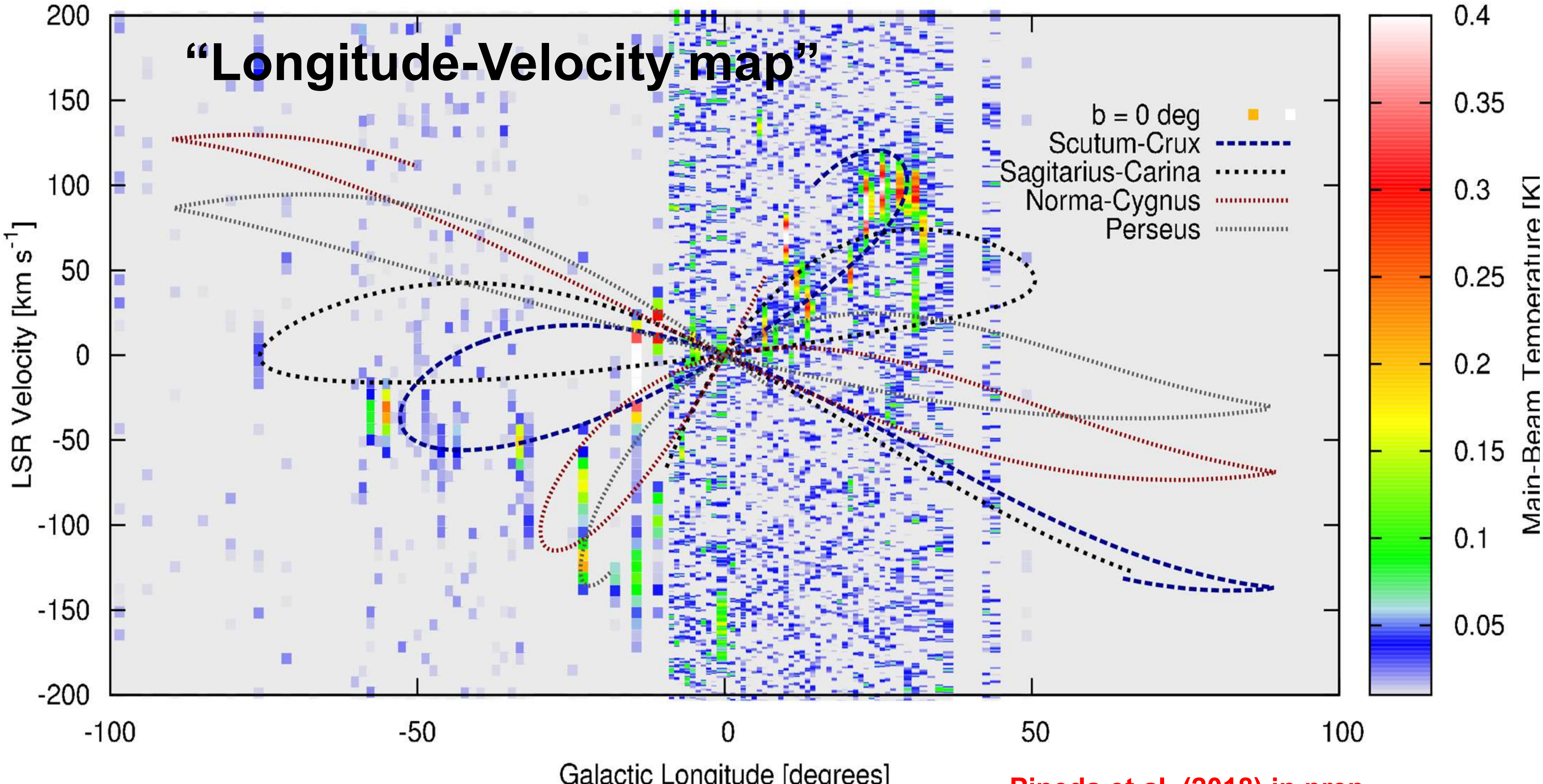
The [CII] distribution of the Milky Way:



Pineda et al. (2013) A&A 554, A103

The lines are projection of the Milky Way's spiral arms into the Longitude-Velocity map.

The [CII] distribution of the Milky Way:

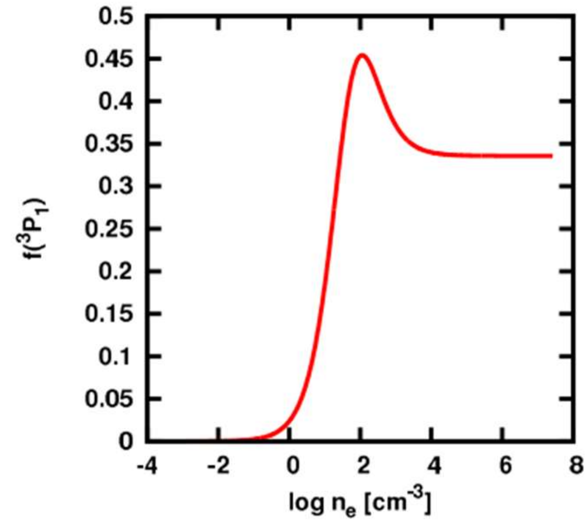


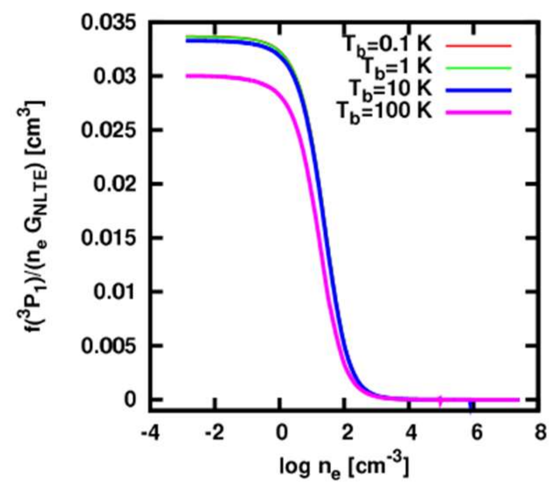
Pineda et al. (2018) in prep.

The lines are projection of the Milky Way's spiral arms into the Longitude-Velocity map.

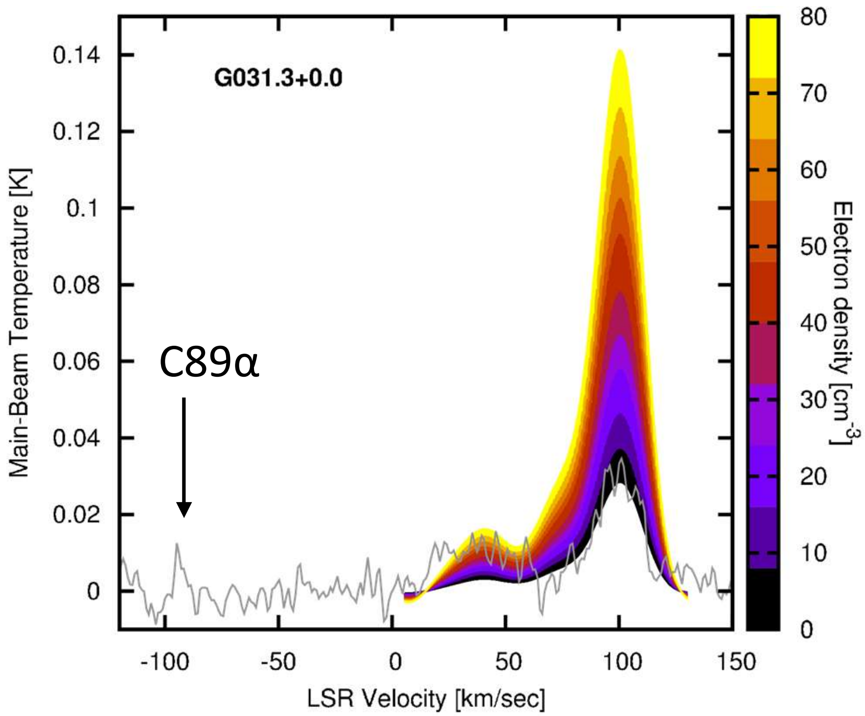
[NII]/RRL ratio as a tracer of electron density.

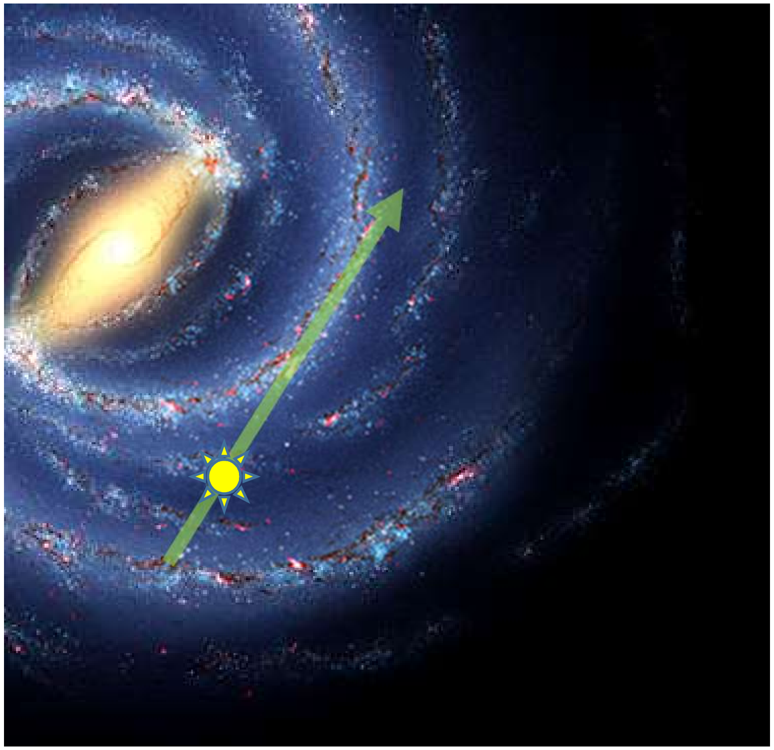
- [NII] 205um intensity is proportional to the fractional population at the $^3P_1$ level, $f_u(ne)$, which depends on the electron density, and the column density of N^+.
- The RRL intensity is proportional to the electron density times the column density of H^+.
- In LTE, the [NII]/RRL ratio is proportional to $f_u(ne)/ne$ times the nitrogen abundance. Correction needed for non-LTE effects needed.
- We can use the [NII] 205um/RRL ratio to solve for the electron density of the gas.





Electron Density along the line of sight.





- Color coded spectrum is the expected RRL spectrum for the observed [NII] intensity for a given electron density.
- Large variations in the electron density is observed along the line-of-sight.
- In this LOS there is a dense HII region at 50 km/sec and a diffuse region at 100 km/sec.

Pineda et al. 2018 in prep.

SOFIA Joint Impact Proposal:

A complete velocity resolved 3-D [CII] map of the M51 grand-design spiral galaxy:

Unraveling the impact of spiral density waves on the evolution of the ISM and star formation

Jorge L. Pineda (US PI), Jurgen Stutzki (DE PI), Paul Goldsmith, Christian Fischer, Maria Kapala, Jin Koda, Christof Buchbender, Bhaswati Moorkejea, Carsten Kramer, Monika Ziebart, Nick Scoville, Ralf Klessen, Rowan Smith, Simon Glover, Karin Sandstrom

SOFIA [CII] Mapping of M51: Science Goals

- Study the effect of spiral arms in the evolution of the ISM and star formation
- Separate the different ISM phases in spiral arms (velocity space).
- Determine the physical conditions of the line-emitting gas over different environments.
- Image the distribution of CO-dark H_2 gas across M51. In particular in the inter-arm regions.

In spiral arms Giant Molecular clouds (where star formation takes place) can form the agglomeration of HI clouds (Classic Picture).

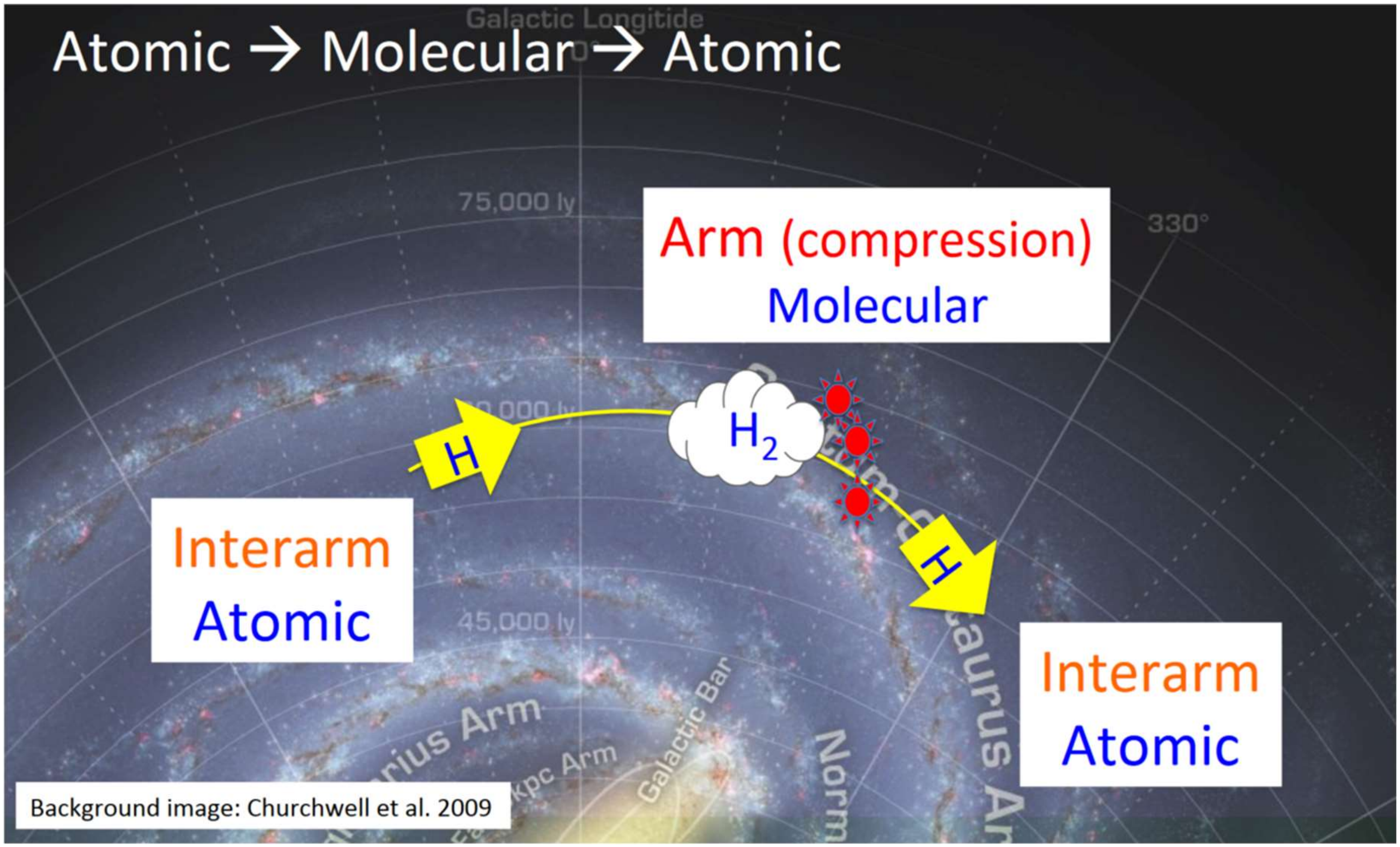
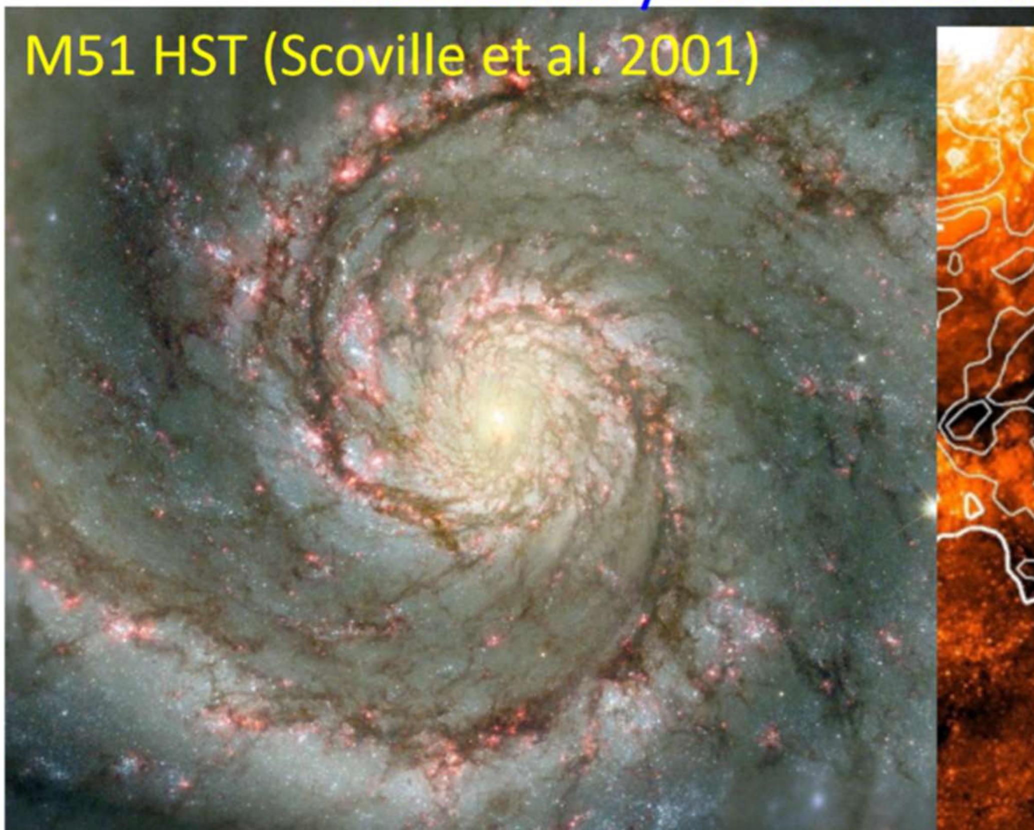
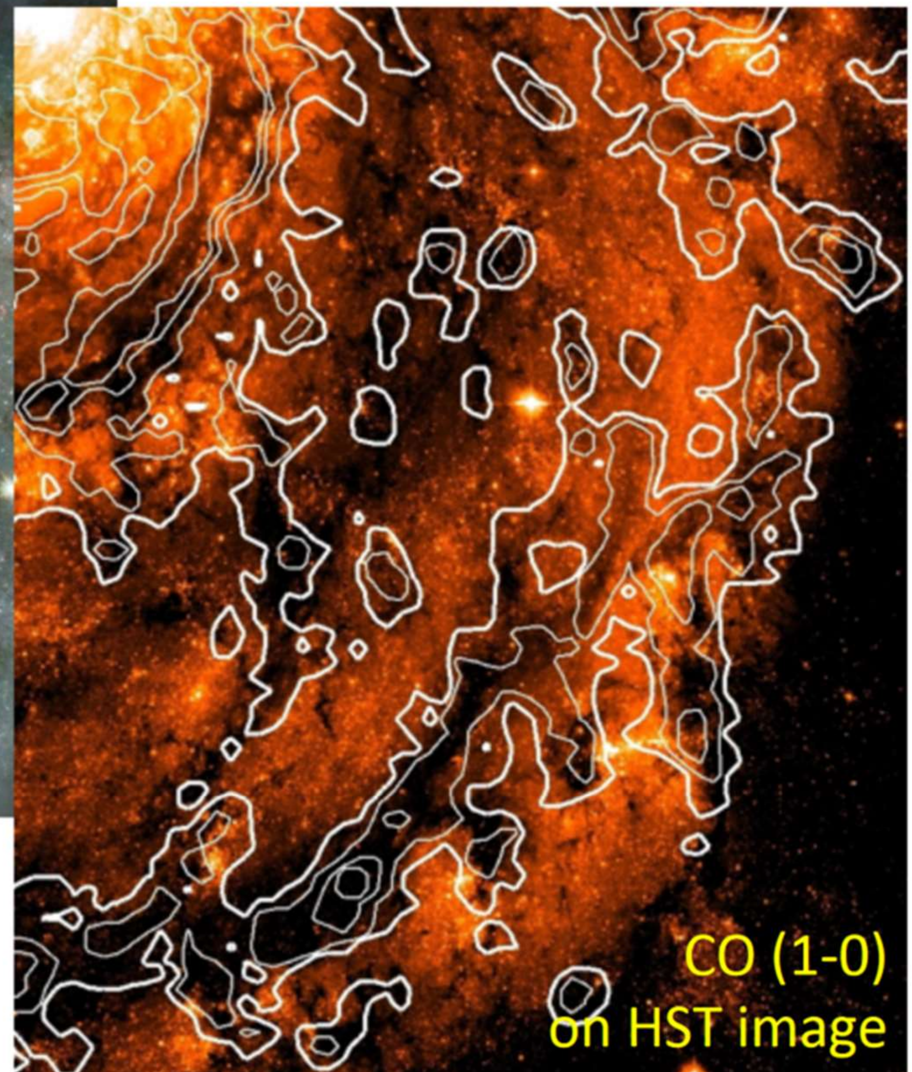


Image courtesy of Jin Koda

Spurs/Feathers in CO(1-0)

Filamentary structures in interarm regions





Spurs = chains of GMCs

Koda et al. 2009

Koda et al. 2009 proposes that molecular clouds are formed from the agglomeration of smaller molecular clouds.

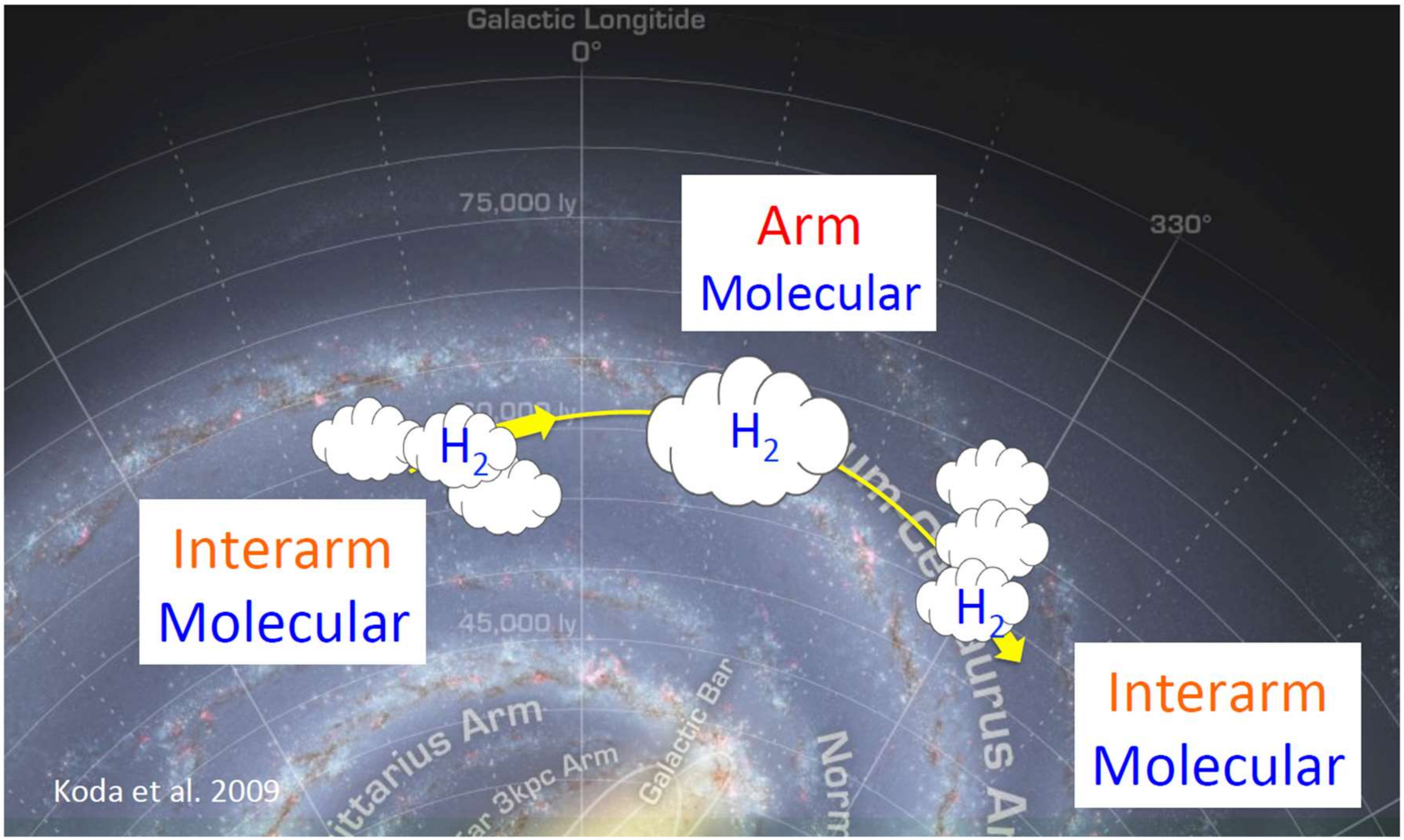
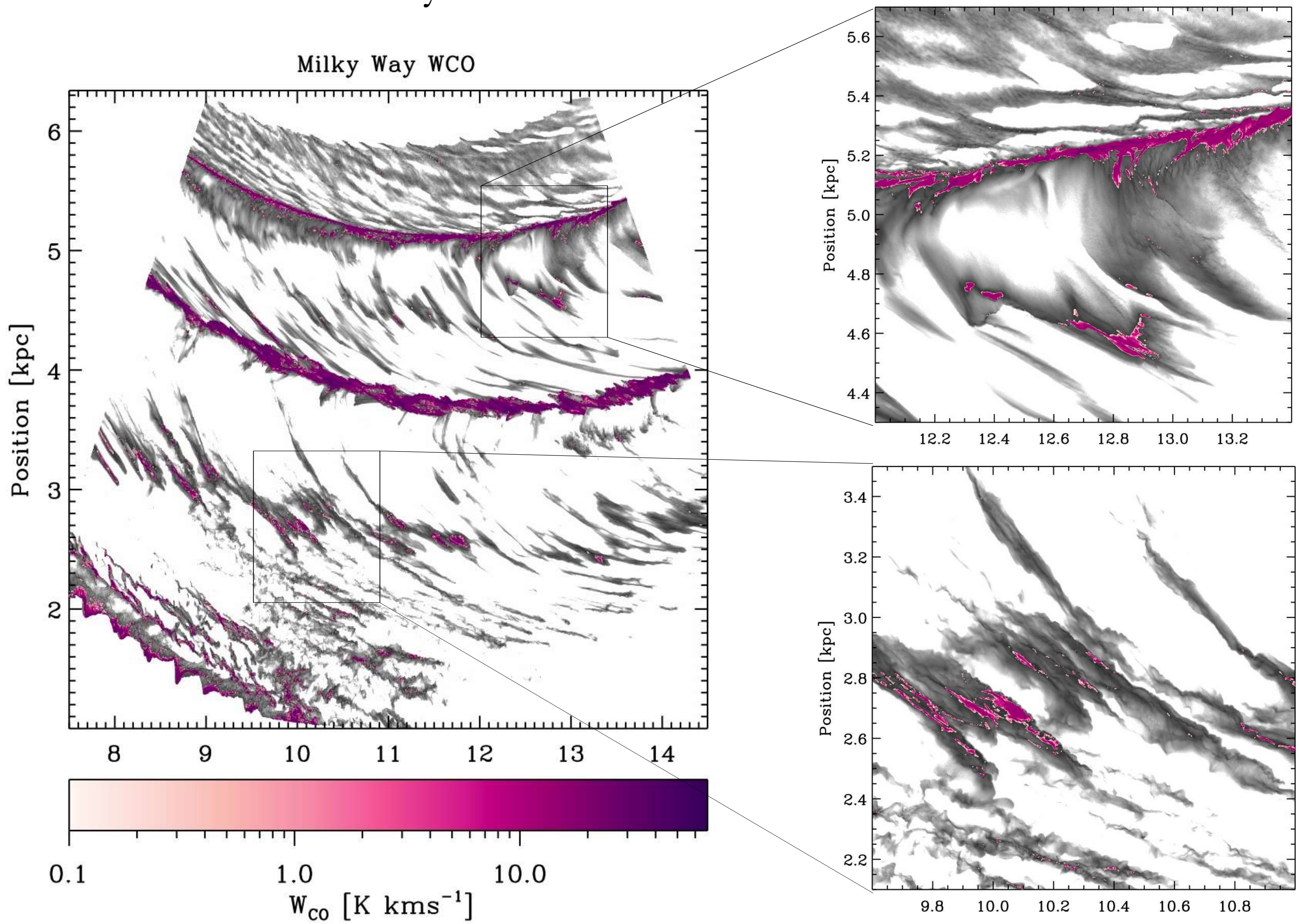


Image courtesy of Jin Koda

Grey-scale: Molecular Hydrogen H_2.
Color-scale: CO Intensity.

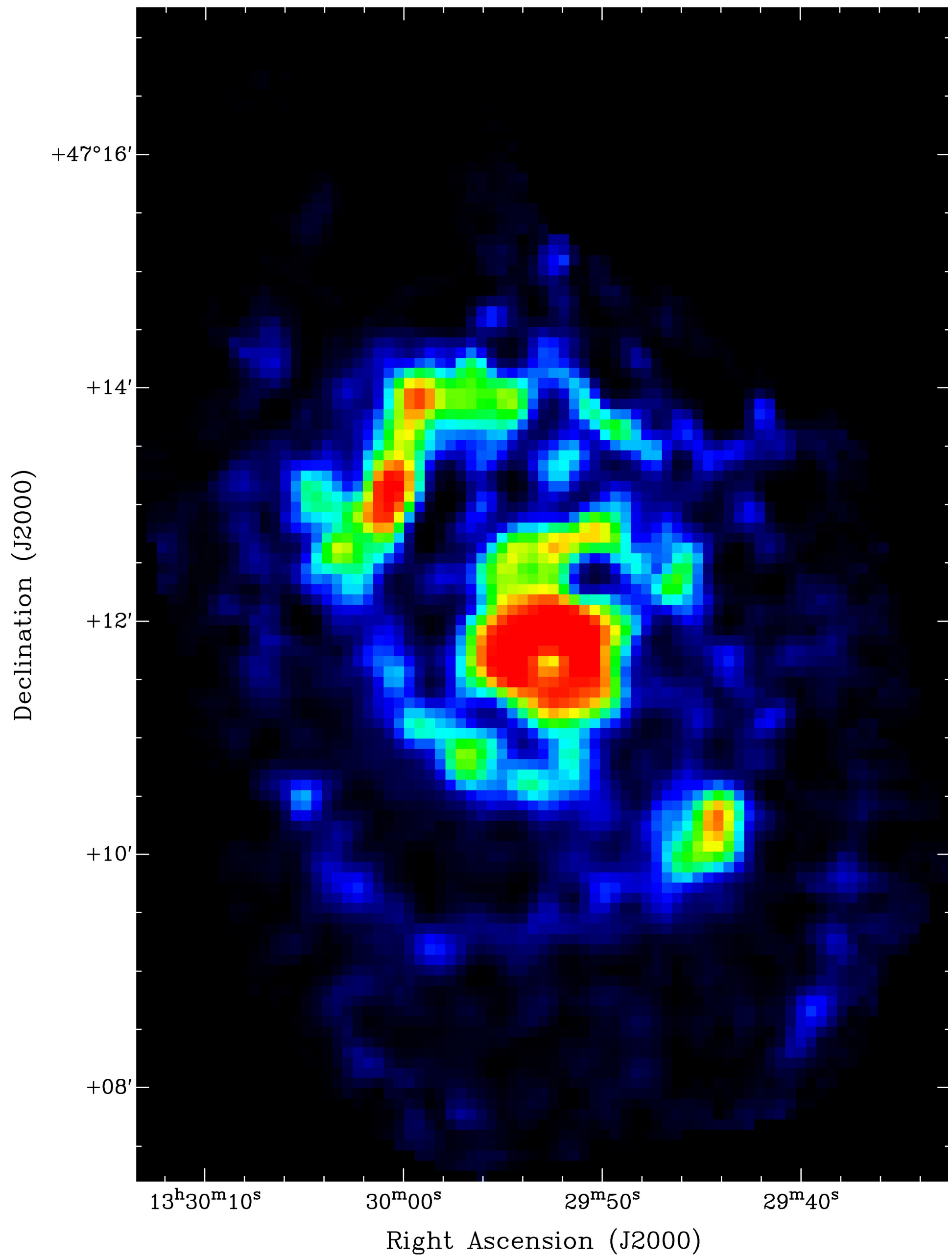


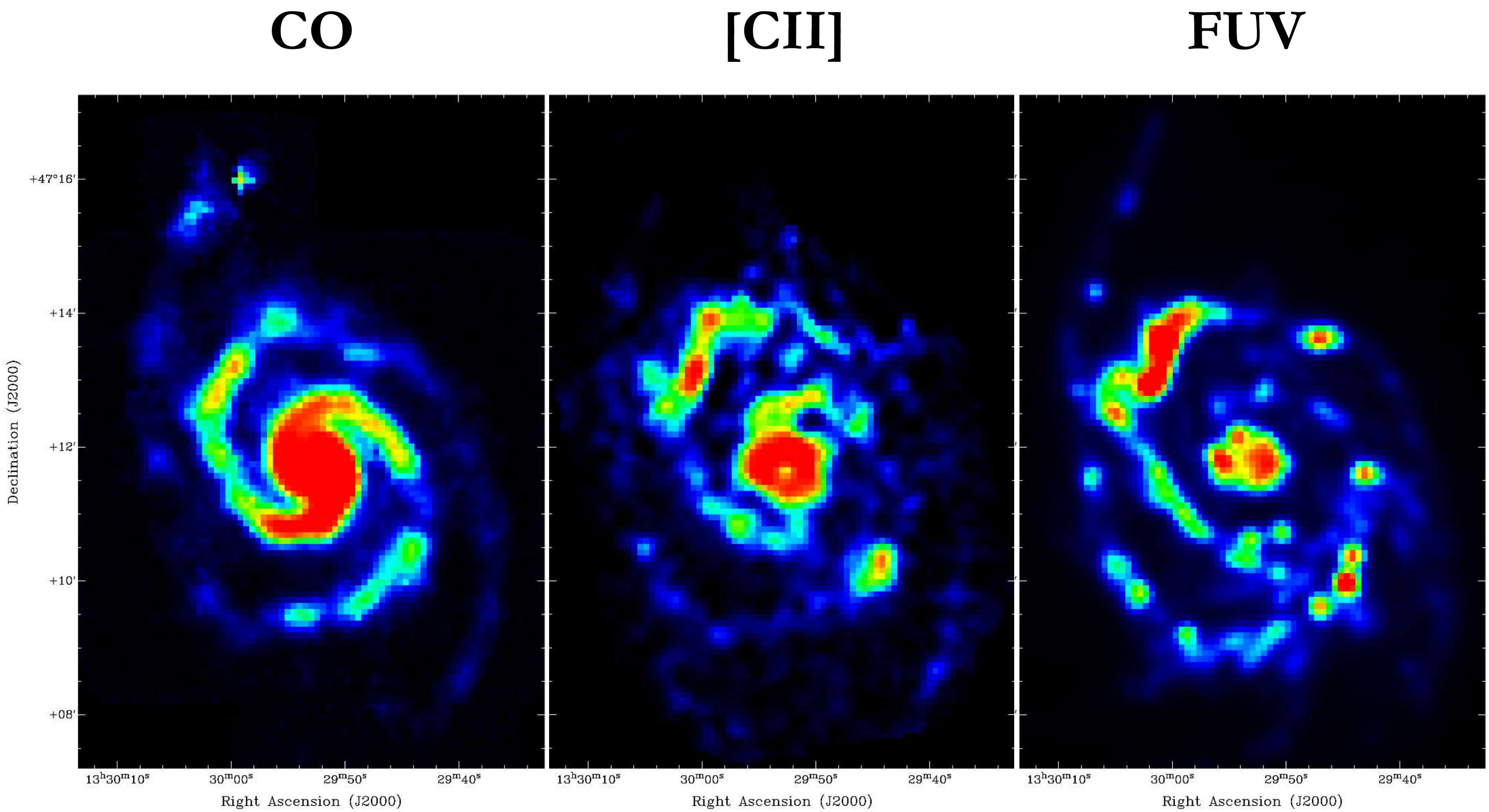
(Smith et al., 2014, MNRAS, 441, 1628)

[CII] Map

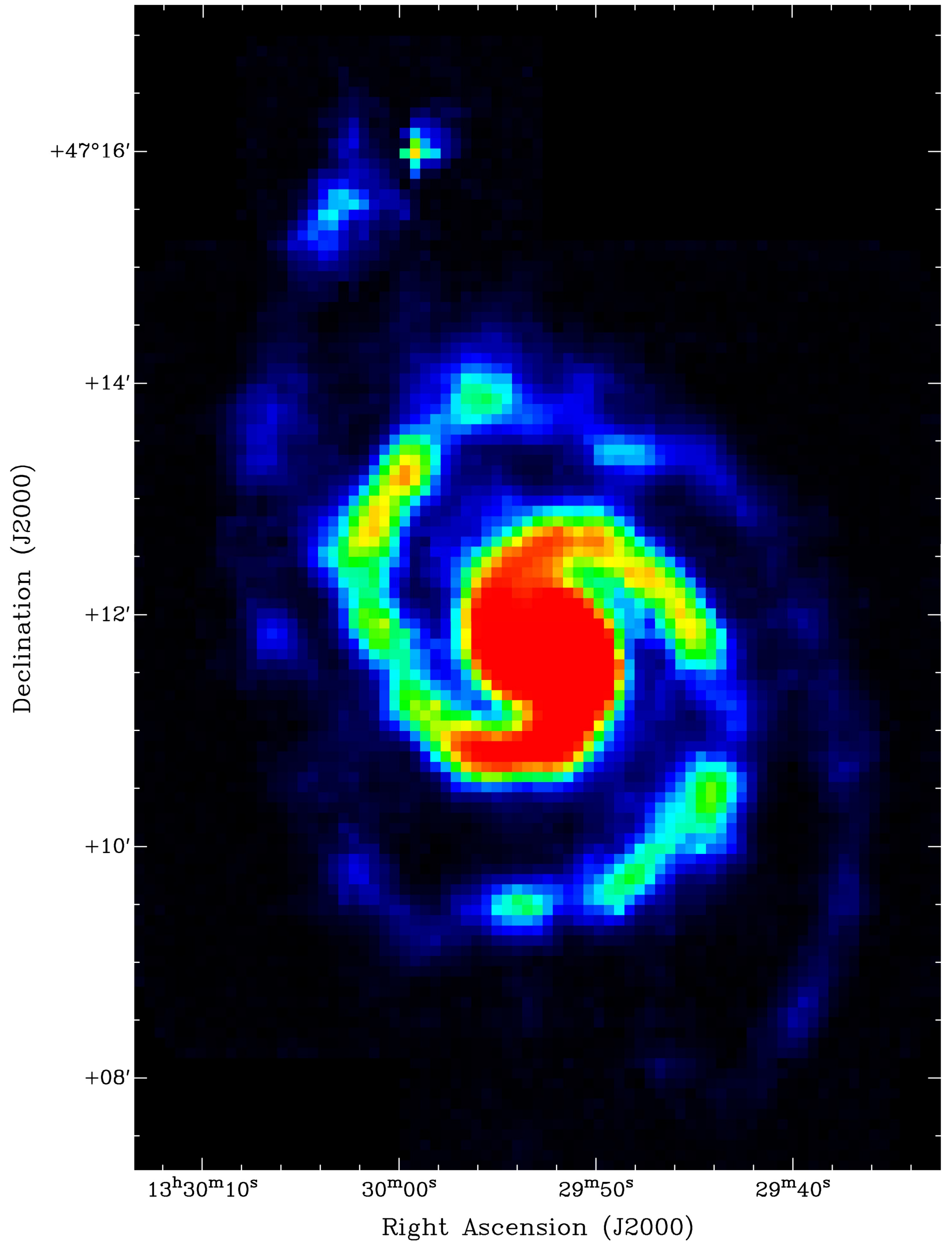
- Joint impact project between US and German institutions.
- 75h of observing time over Cycle 4 and 5.
- 80% US time and 20% German time.
- **upGREAT** observations for resolving the spiral arms in velocity space.
- **FIFI-LS** observations for sensitive observations of [CII] in the inter-arm regions.
- Expected completion, February 2019.

upGREAT Map of M51

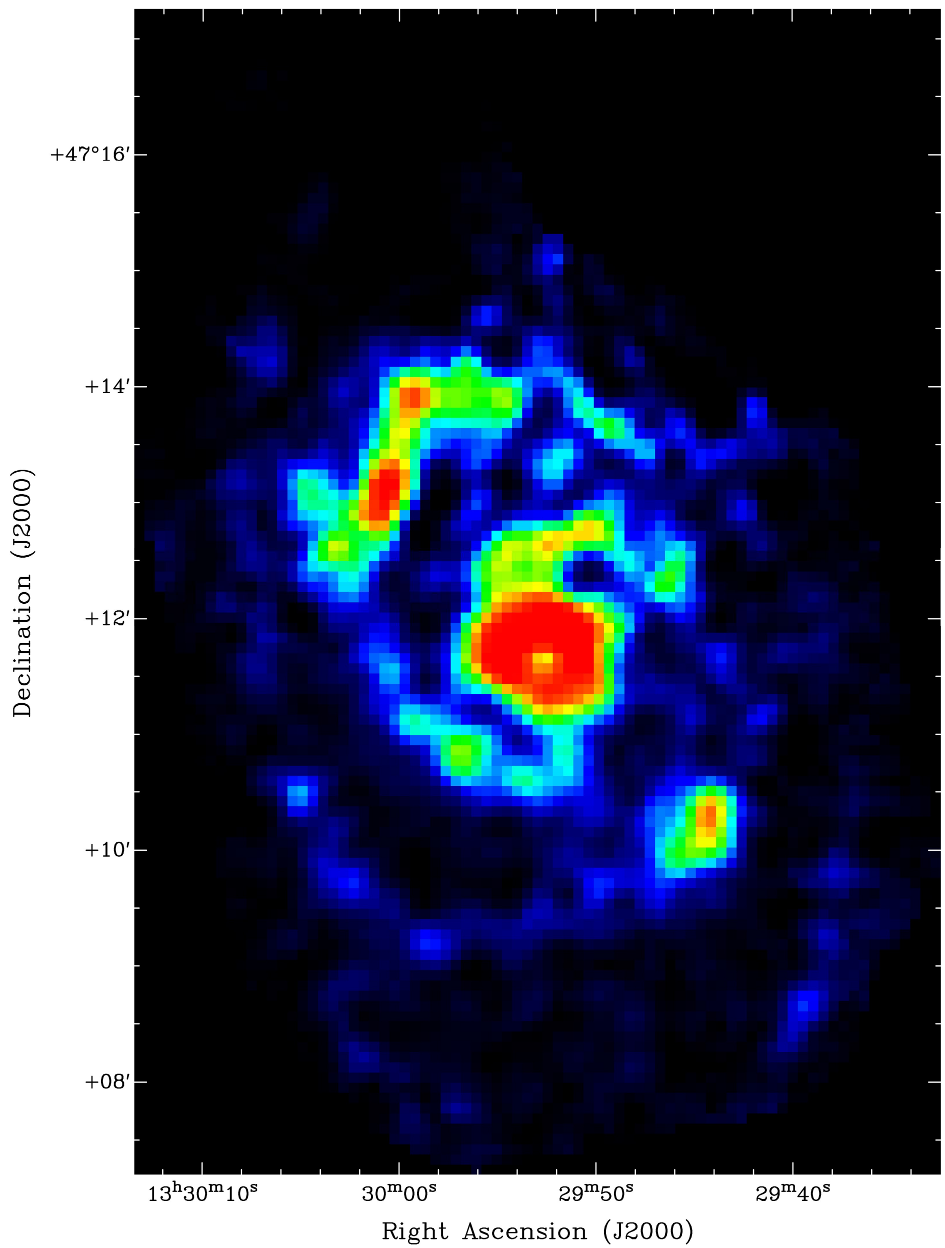




- There are spatial offsets between UV, [CII], and CO observations. [CII] peaks between the UV and CO emission.



+47°16′
+14′
+12′
+10′
+08′
Declination (J2000)
13h30m10s
30m00s
29m50s
29m40s
Right Ascension (J2000)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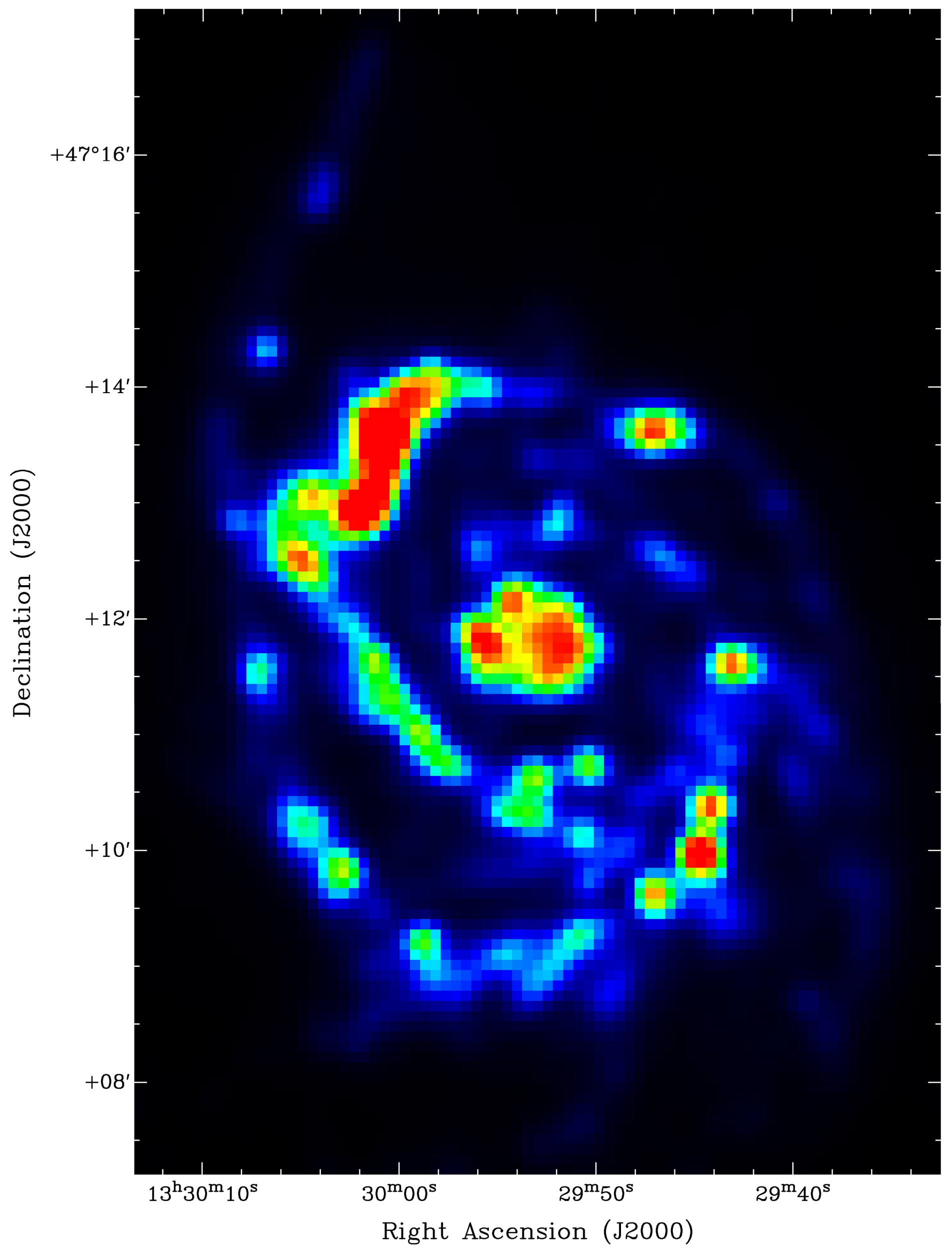

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Declination (J2000)
13h30m10s
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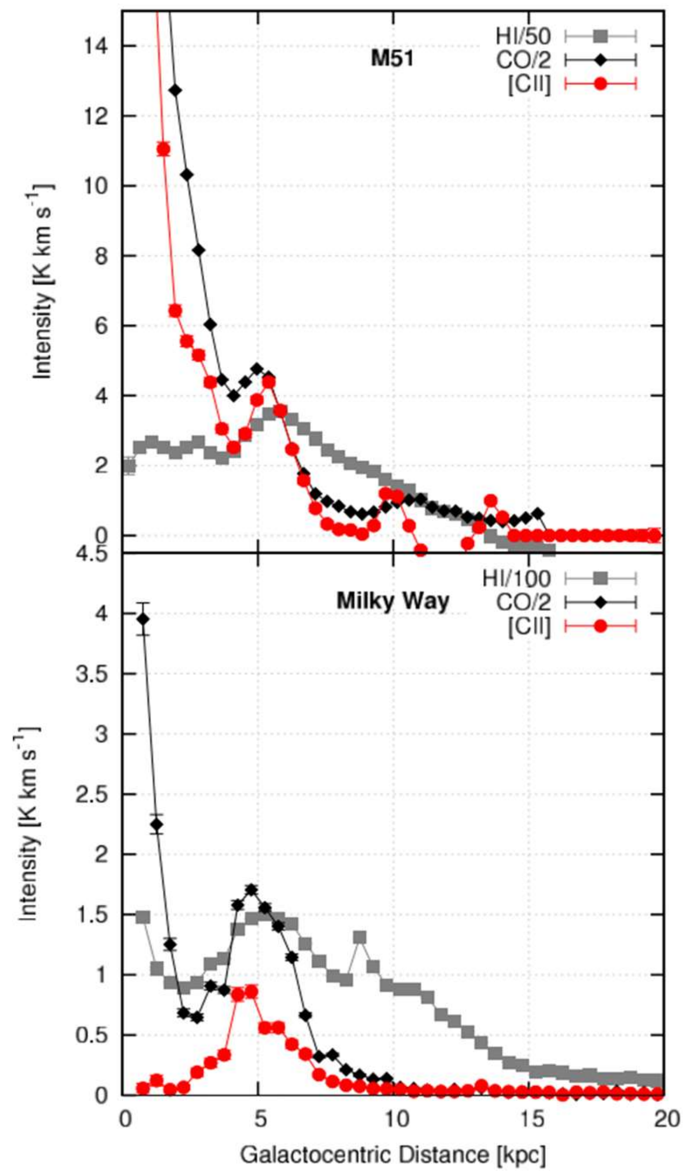
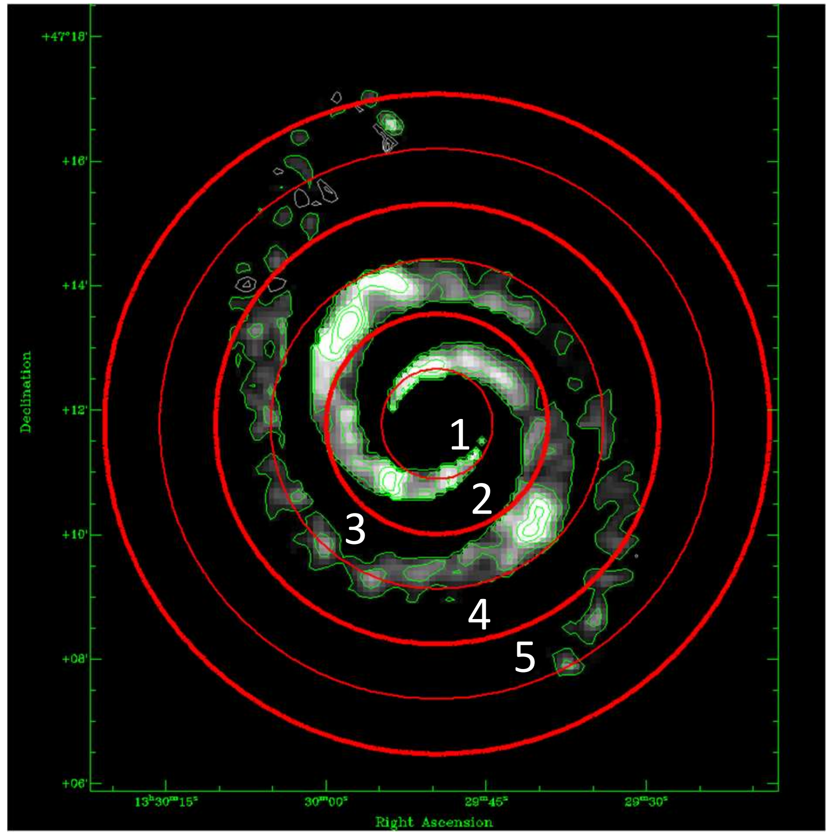
Radial Distribution of HI, CO, and [CII] in M51.

- The radial distribution of [CII], HI, and CO in M51 is similar to that of the Milky Way.
- [CII] peaks at about 4 kpc, where two prominent star forming regions are located.
- [CII] extends mostly over the inner 10 kpc of the galaxy.



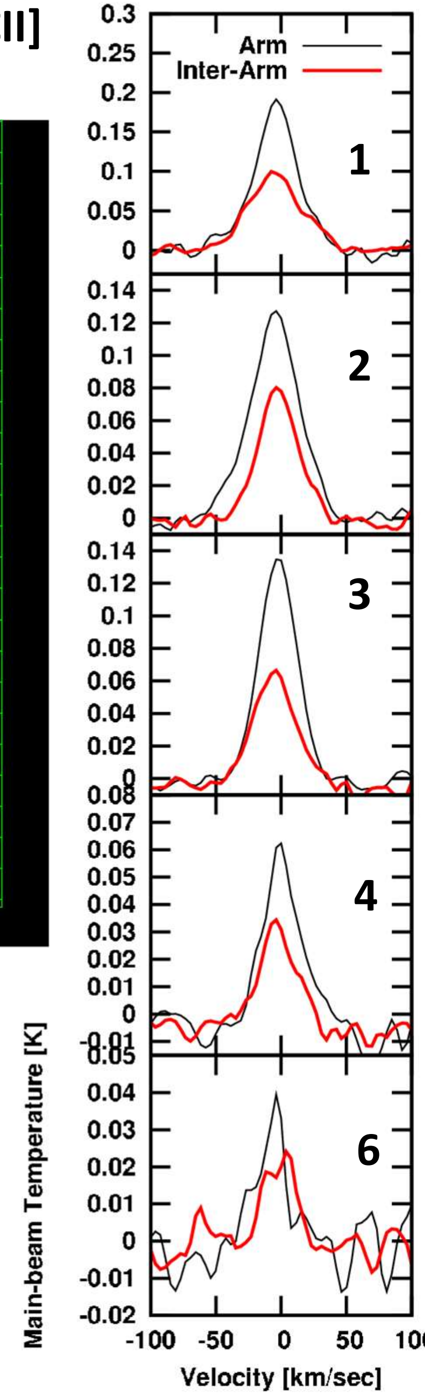
Arm vs Inter-arm regions

- Stacked spectra in radial bins show that [CII] emission in present in both arm and inter-arm regions over **all** surveyed area.
- There is a widespread diffuse [CII] component present in inter-arm regions.



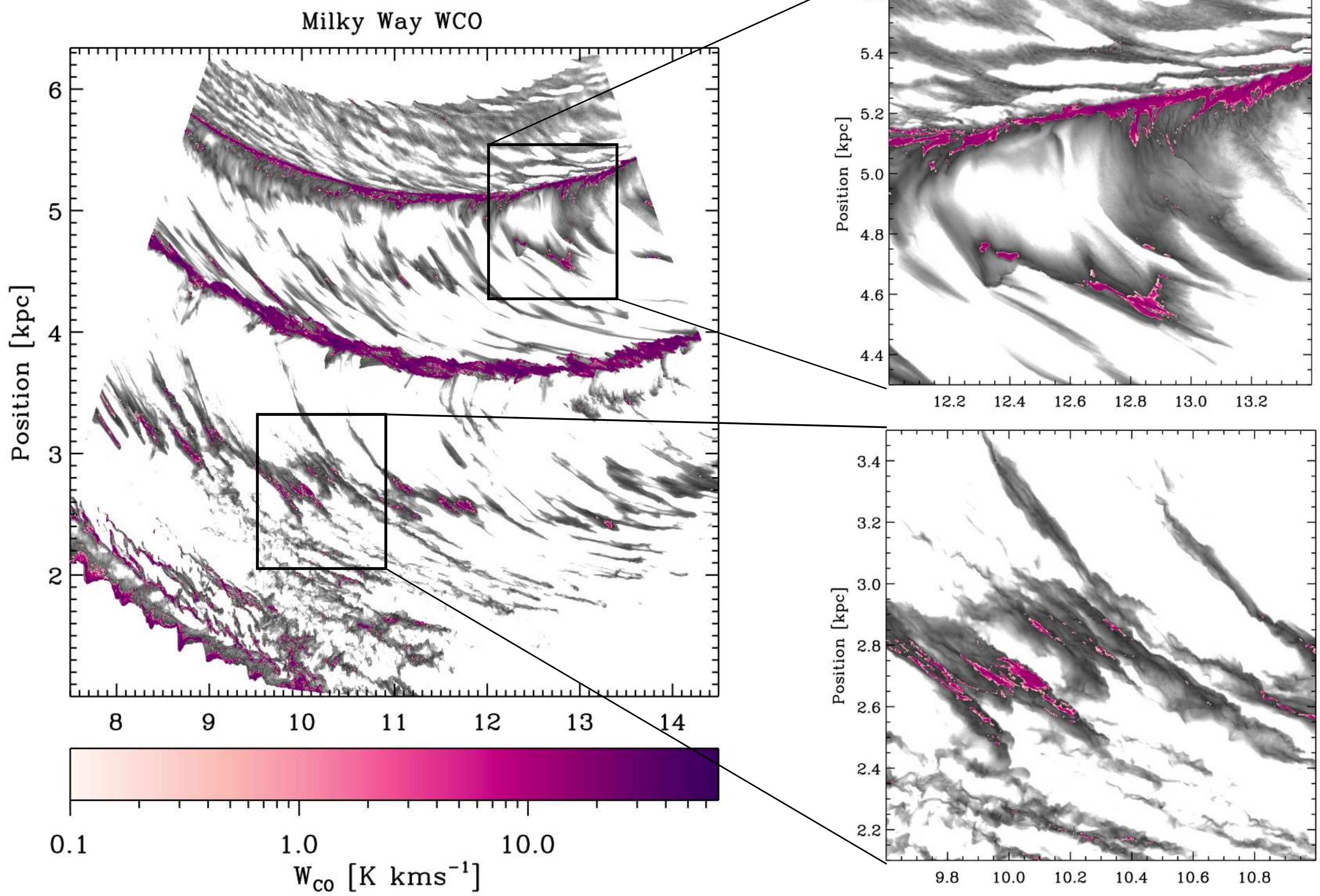
The galaxy center and companion were masked out.

[CII]



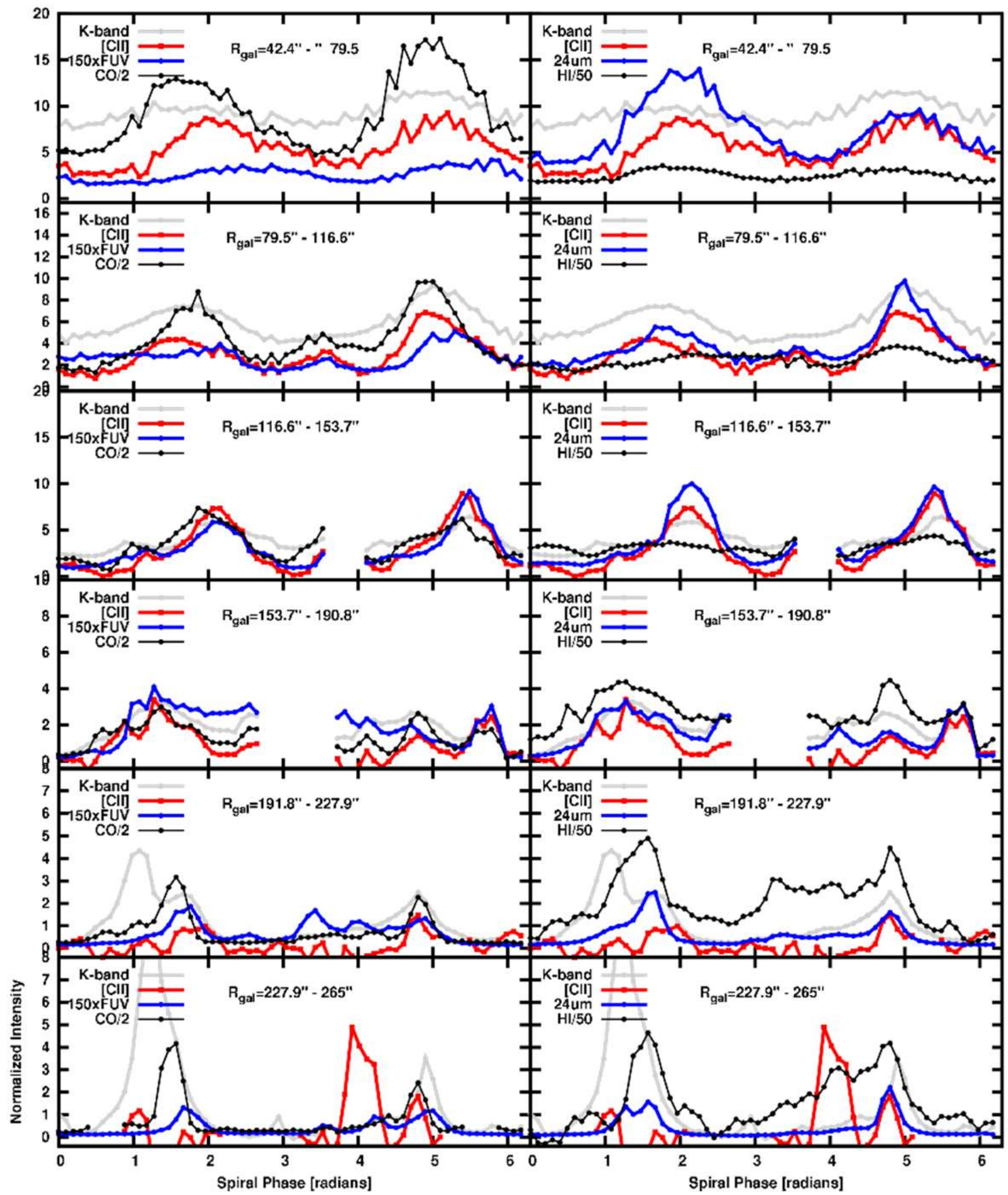
- Presence of widespread [CII] emission in spiral arms is in agreement with predictions of numerical simulations that predict large amounts of CO-dark H_2 in inter-arm regions (H2 gas is shown in grey below).

Smith et al. 2014

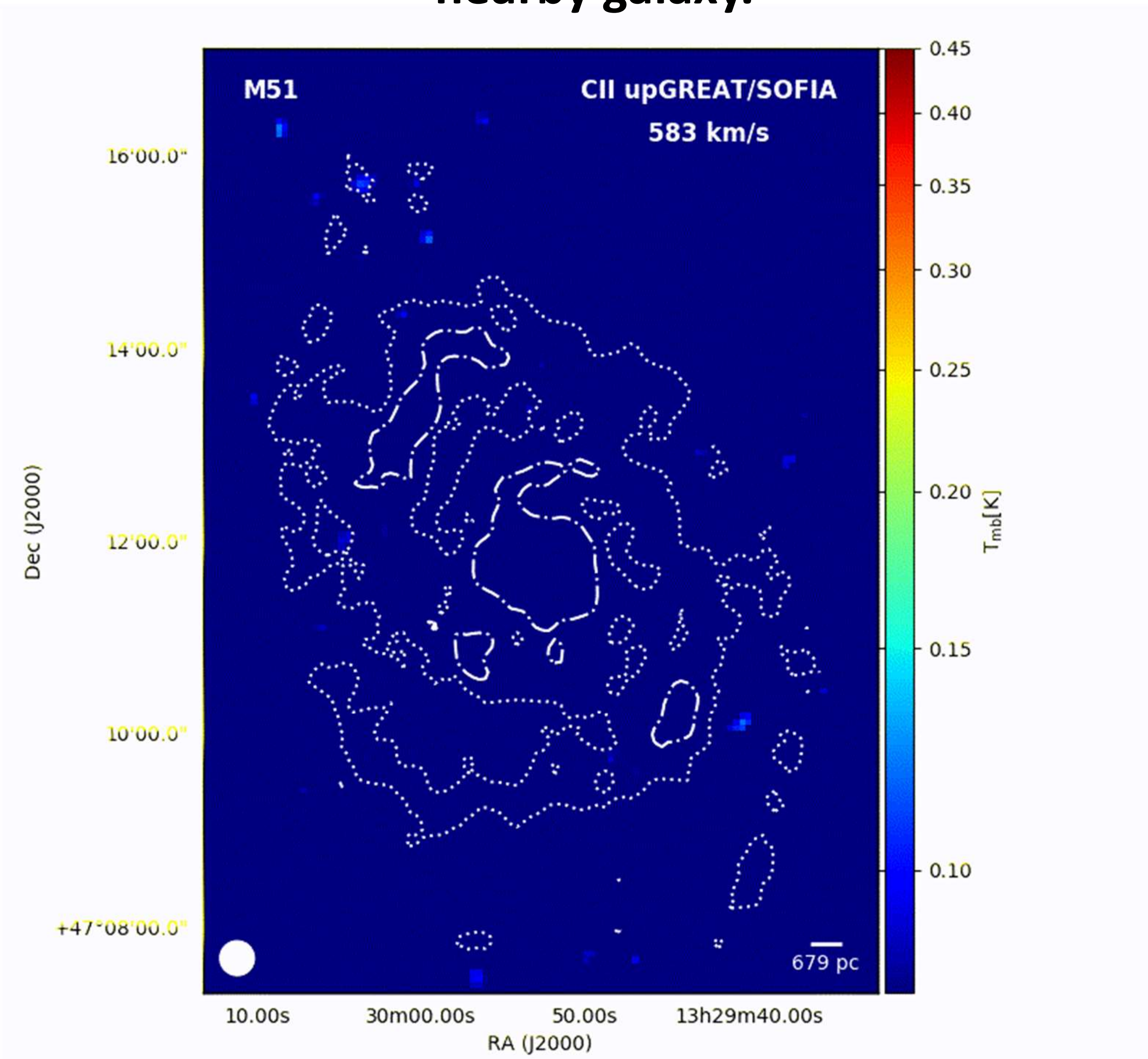


[CII], CO, FUV, etc variation across arms.

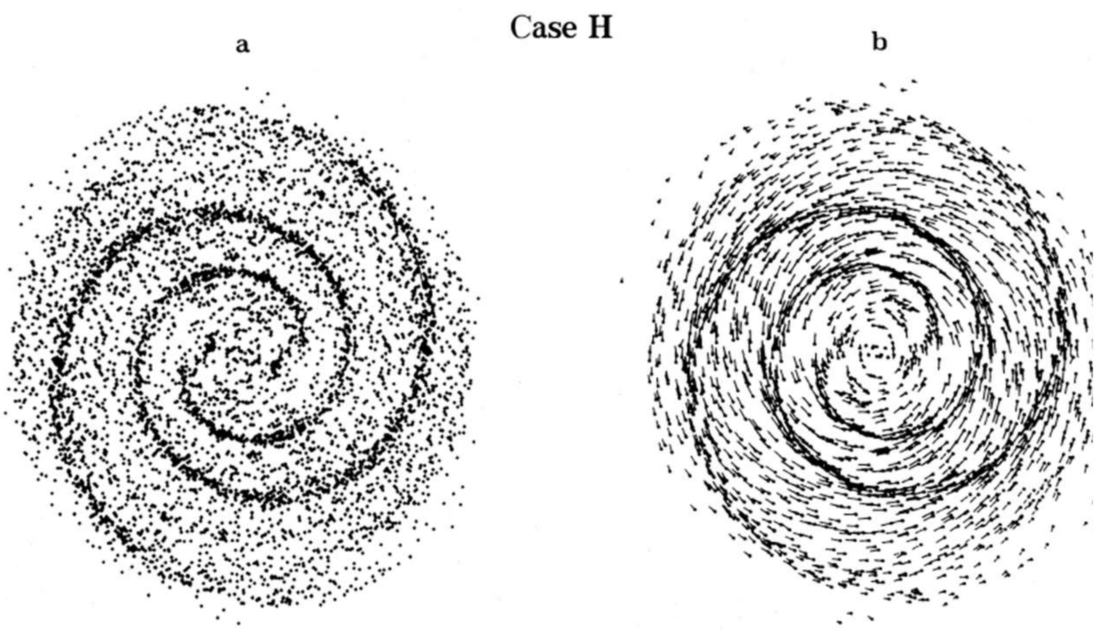
- There is a systematic variation of the CO, [CII], and FUV peaks across spiral arms.
- Molecular clouds (CO) -> Star formation ([CII]) -> cloud dispersion (FUV).
- If the lag varies systematically with Galactocentric radii, the lag between the tracers can be used to estimate the time scale of ISM evolution.
- No clear radial trend found in the data.



The M51 map is the first spectrally resolved map of a complete nearby galaxy.



Spiral Density Waves



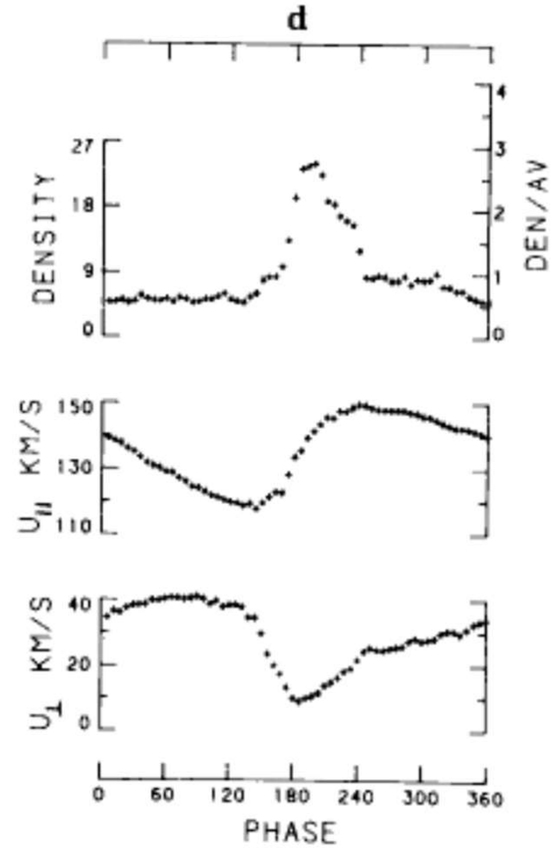
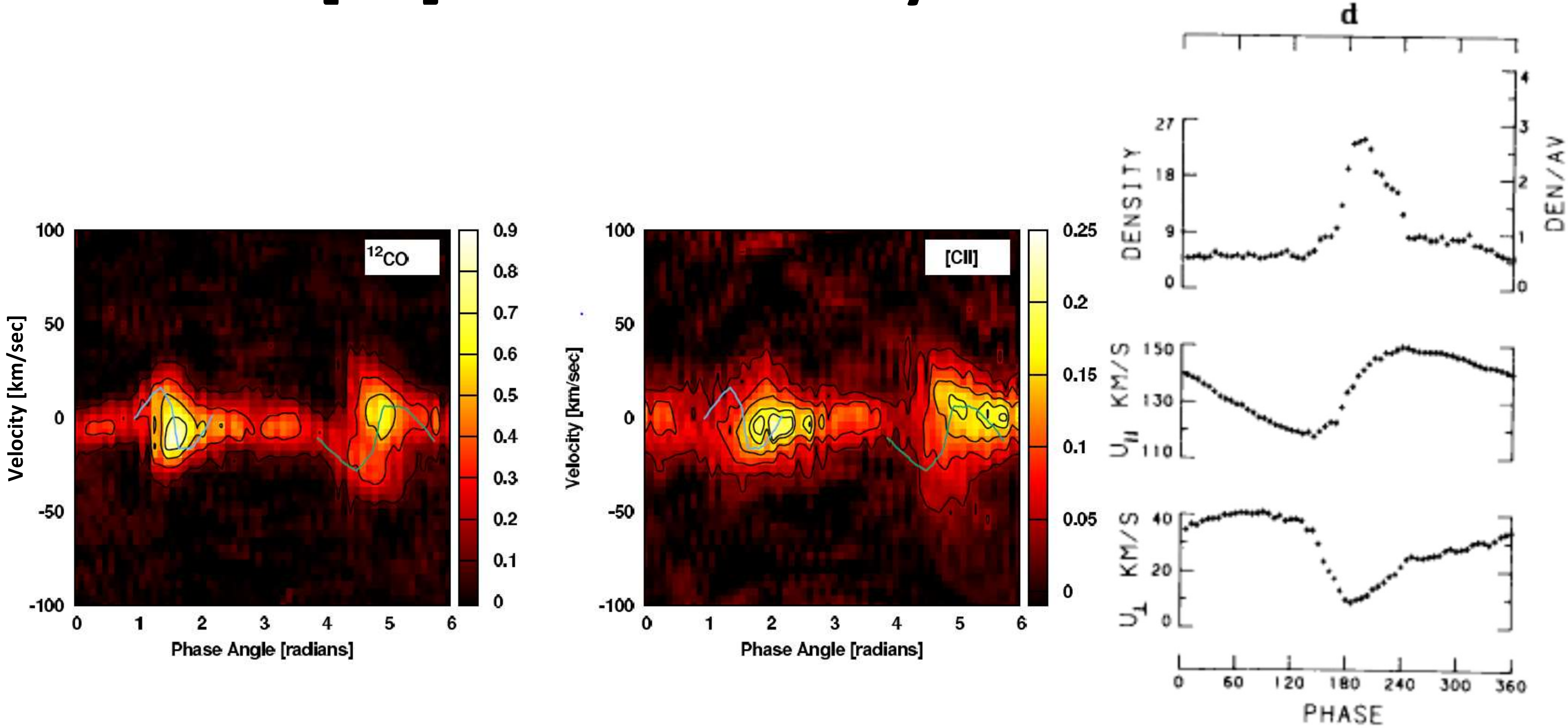


FIG. 5.—Cloud density (*top*) and velocity components (*middle*, tangential; *bottom*, radial) plotted vs. spiral phase, from RS87 dissipative simulations, case M. For a tightly wound spiral, a cut through the spiral phase is roughly equivalent to a cut in radius. This particular figure is at a time step 1170 Myr.

Roberts et al. 1987. See more modern calculations by Baba 2016

[CII] and CO velocity structure.

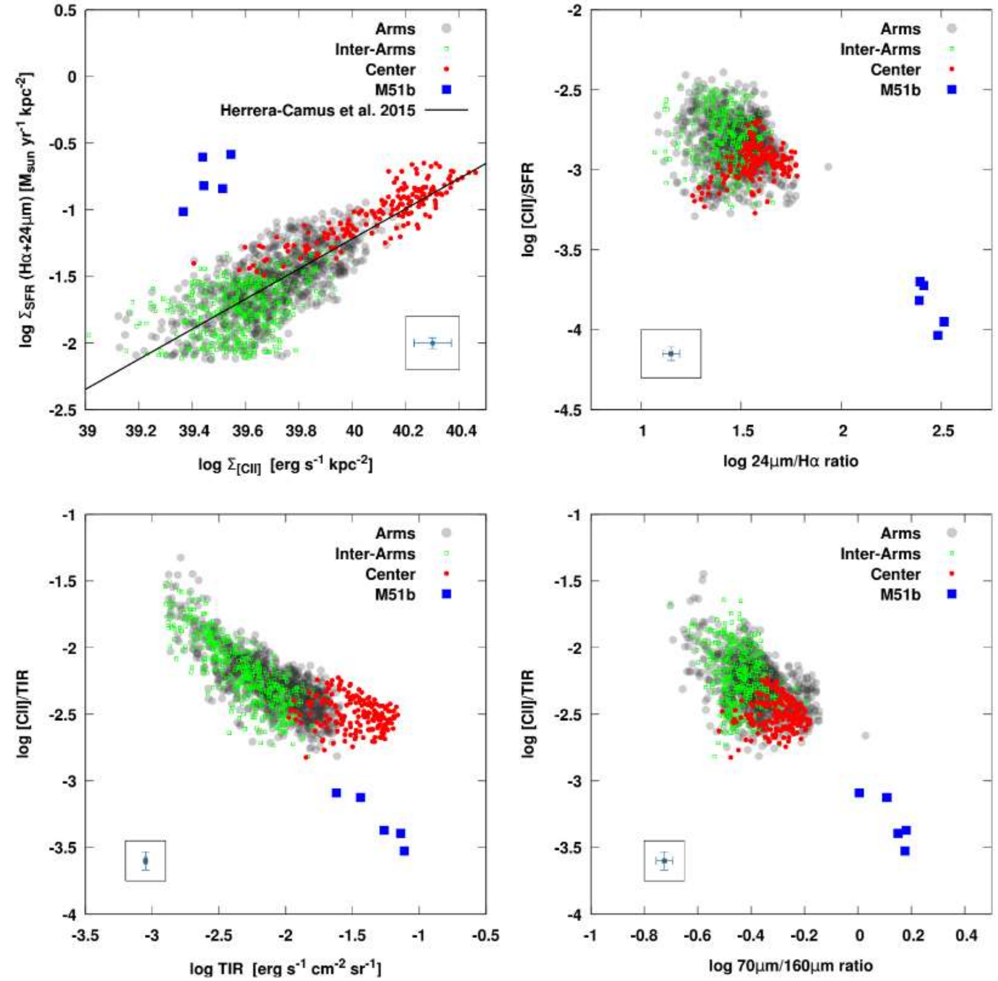


- Position Velocity Maps across spiral arms show velocity discontinuities that are possible related to spiral shocks.
- CO is being agglomerated/compressed and peak the end of the discontinuity.
- [CII] peaks right after the CO peak, suggesting that the discontinuity triggers star formation.
- Velocity distribution is in good agreement with projected theoretical predictions.
- Velocity resolved observations of [CII] and CO can be used to test theories of spiral structure.

[CII] as a tracer of star formation over different environments in M51

- [CII] and the SFR are well correlated in the disk of M51, with a [CII]-SFR relationship that is similar to that in the Milky Way and other nearby galaxies.

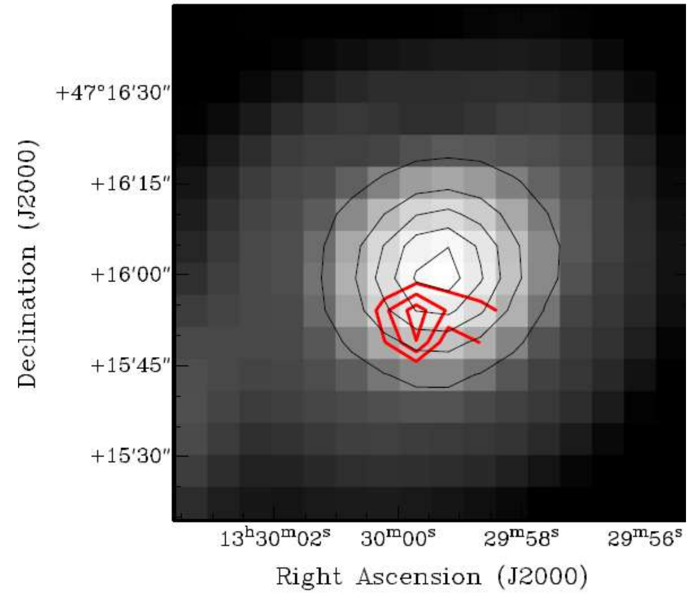
- But the companion galaxy, NGC5195 shows a deficit of [CII] with respect to FIR emission.

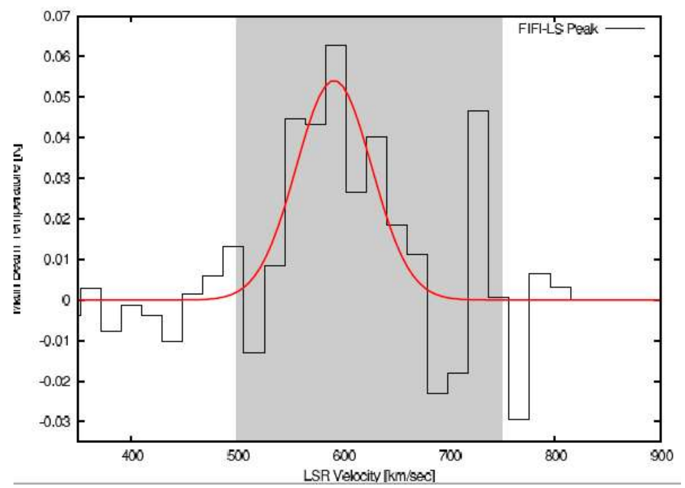


Pineda, Fischer, Stutzki, et al. 2018, soon in press

[CII] as a tracer of star formation over different environments in M51

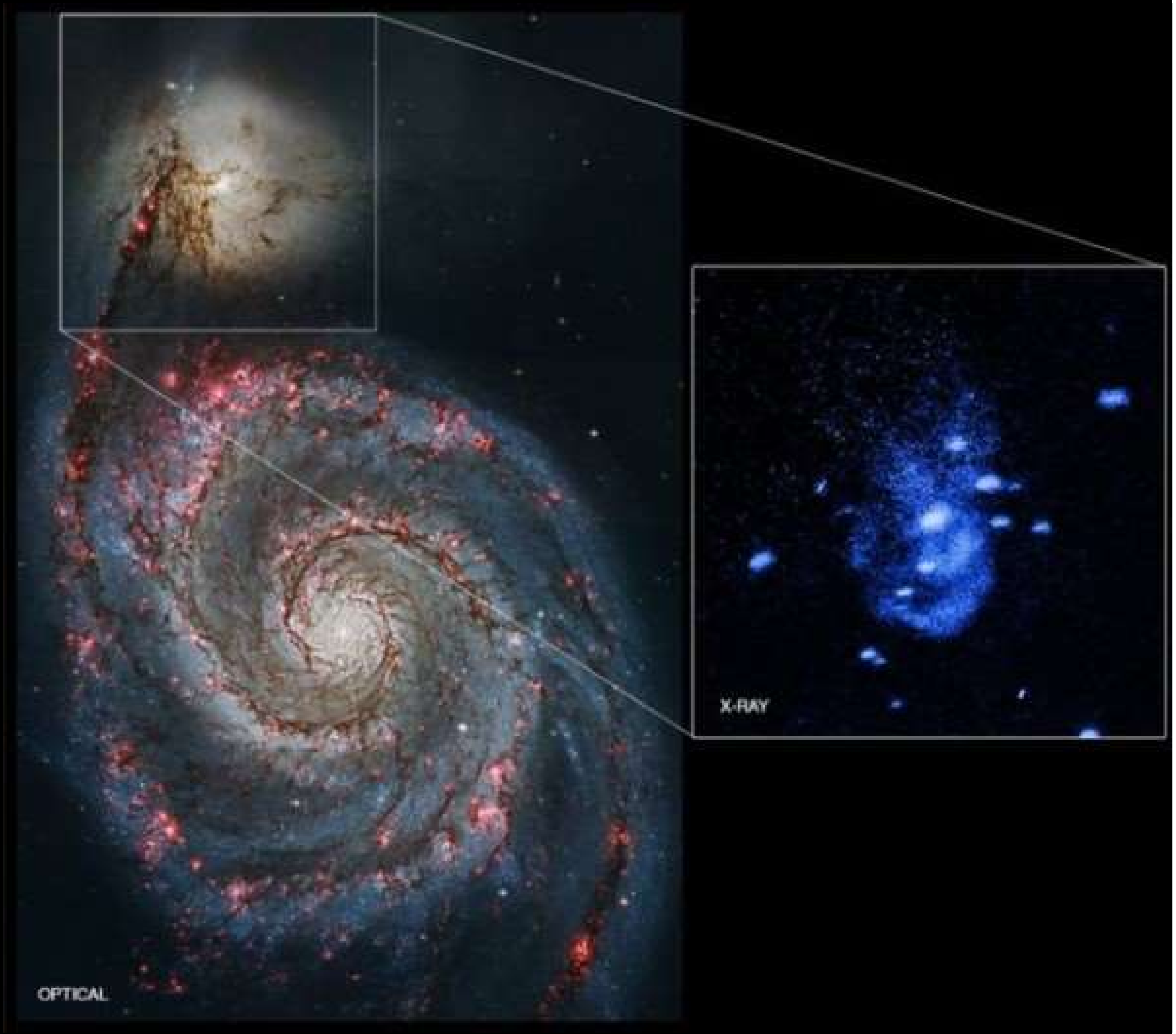
- [CII] and the SFR are well correlated in the disk of M51, with a [CII]-SFR relationship that is similar to that in the Milky Way and other nearby galaxies.
- But the companion galaxy, NGC5195 shows a deficit of [CII] with respect to FIR emission.
- Faint [CII] is detected in the S—W part of the galaxy.
- Stacked upGREAT spectra in this region show emission at a velocity that is consistent with that of CO.





Pineda, Fischer, Stutzki, et al. 2018, soon in press

- The closest super massive black hole is in NGC 5195.
- X-ray emission shock arcs shows that gas is being pushed away.
- Closest example of AGN feedback.
- AGN activity can power the bright Mid- and FIR-emission in M51b.
- Companion might be an ideal location for studying the [CII] deficit observed in ultraluminos infrared galaxies.



Schlegel et al. 2016

Summary

- The [CII] line is a good tracer of the different phases of the interstellar medium and star formation in galaxies.

- GOT C+ allowed us for the first time to study global properties of clouds in the Milky Way in [CII].

- In the Milky Way [CII] is mostly concentrated in the inner galaxy. We found that about 30% of the molecular gas has been missing in CO surveys.

- In the M51 galaxy, [CII] can be used to characterize the dynamics of the star forming gas and the effect of spiral density waves in the formation of stars.